SuperKEKB operating experience of RF system at high current

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- Overview of SuperKEKB and RF system
- Normal Conducting Cavity –ARES–
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  - Coupled Bunch Instability (CBI)
    - μ=-1, -2 and -3 modes
    - Zero-mode related to Robinson stability
  - Bunch Gap Transient
- 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
- Target Peak Luminosity

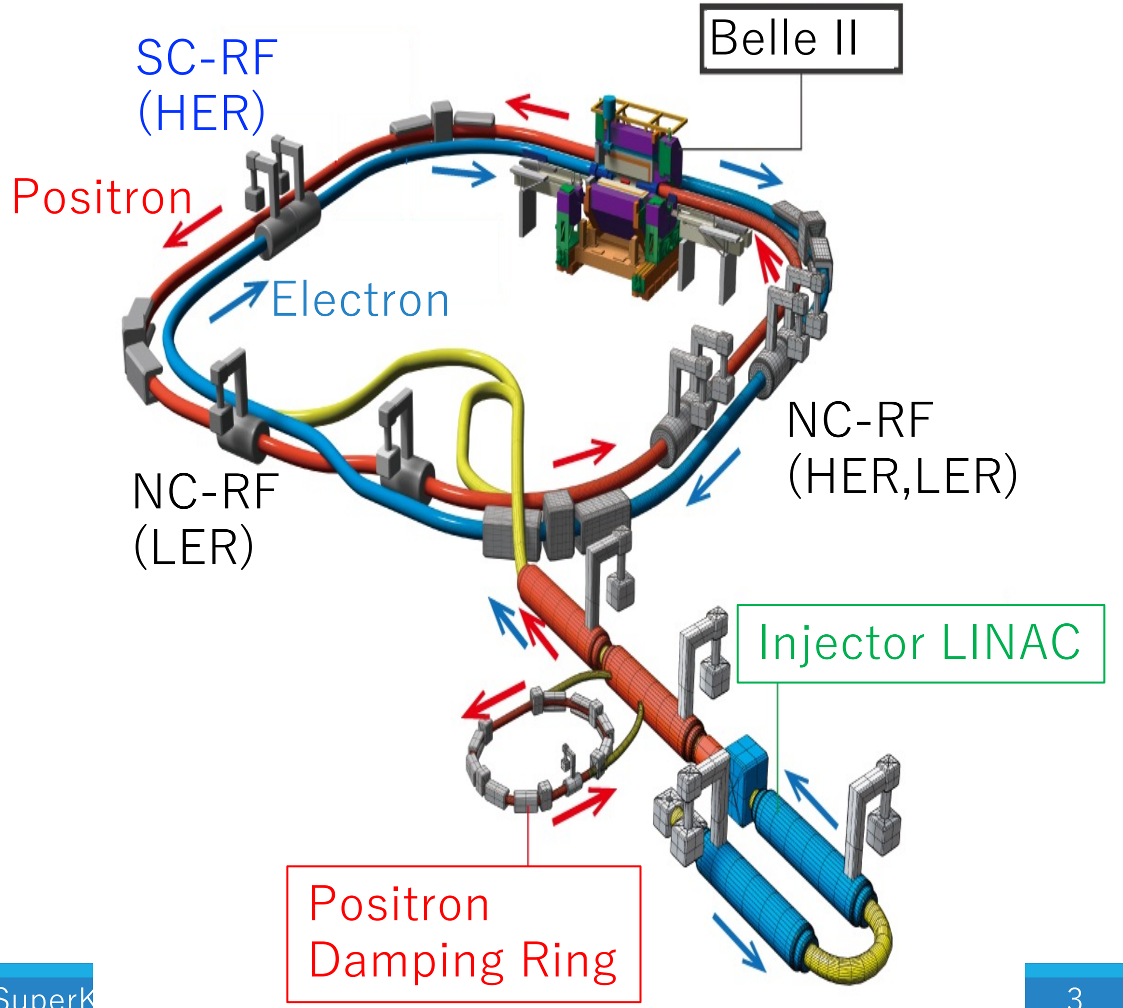
  8×10^{35} /cm^2/s = 800 /nb/s

  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.

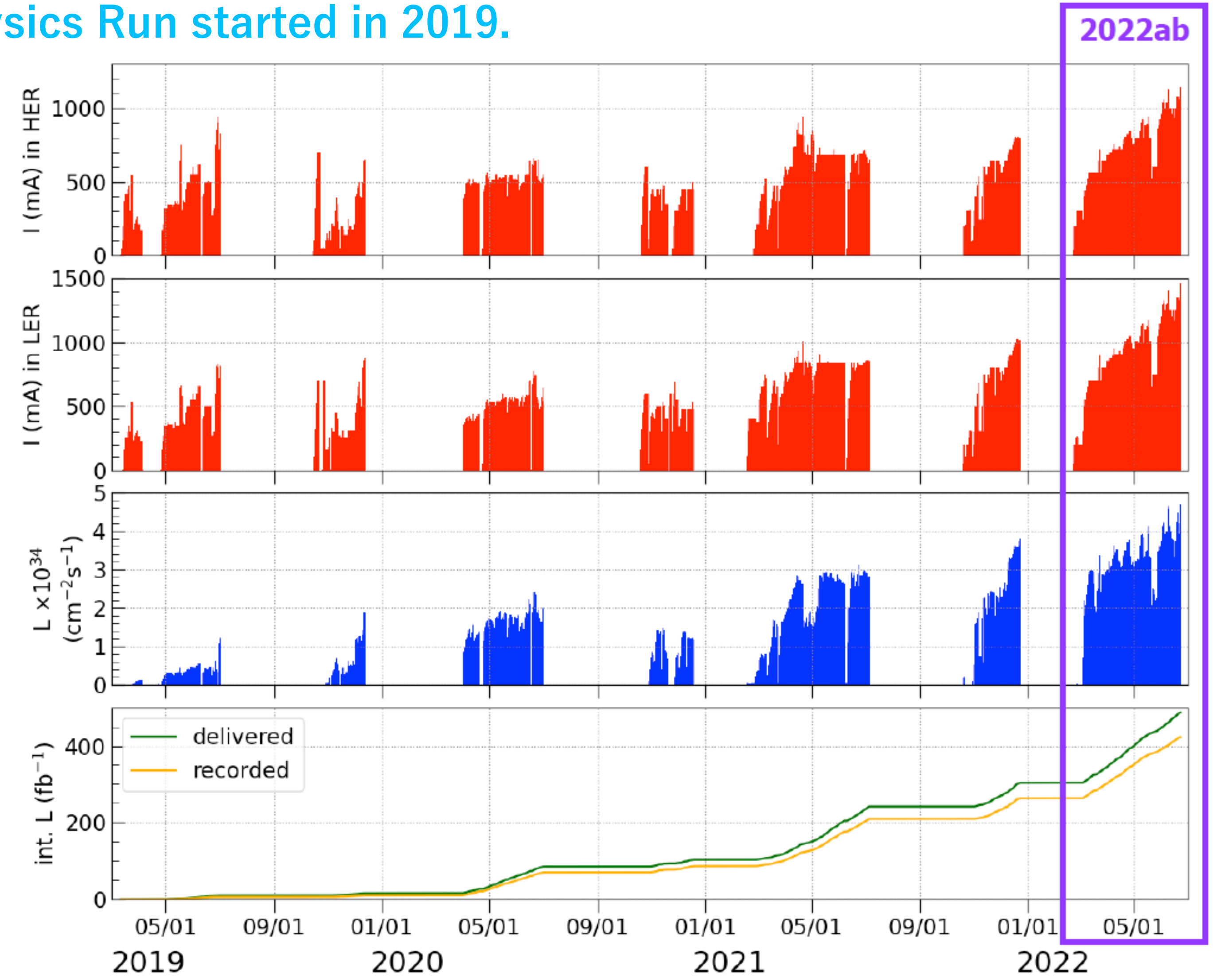
	LER	HER
Particle	positron	electron
Energy	4 GeV	7 GeV
Beam Current (design)	3.6 A	2.6 A



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)

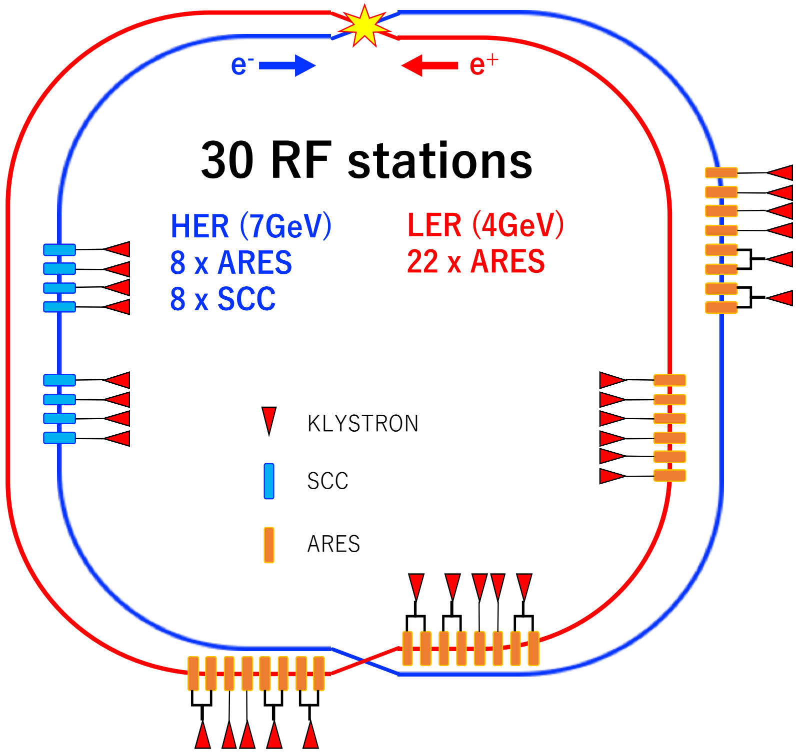
Integrated Luminosity (recorded)

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)				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



Upgrade items

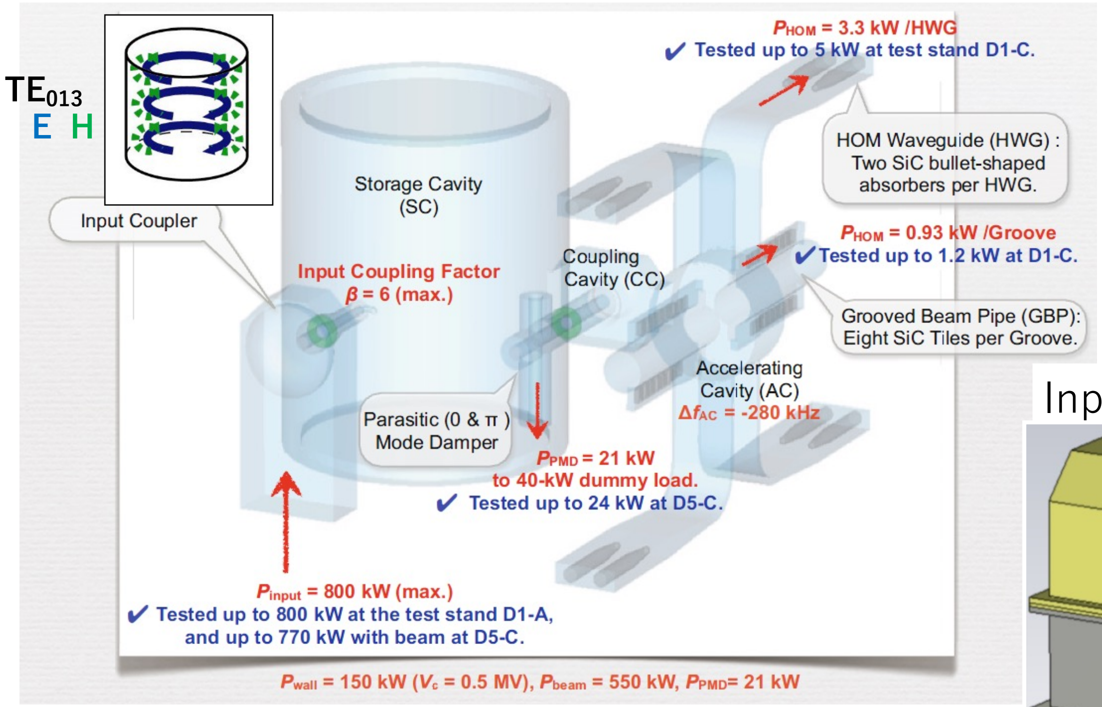
- Increasing the number of RF stations where one klystron drives one ARES (Normal Conducting Cavity), called 1:1 station.
- ARES (Normal Conducting Cavity)
  - Changing Input Coupling β from 3 (1:2) to 5 (1:1).
- SCC (Superconducting Cavity)
  - Installation of additional HOM damper
- HPRF
  - Replacement 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

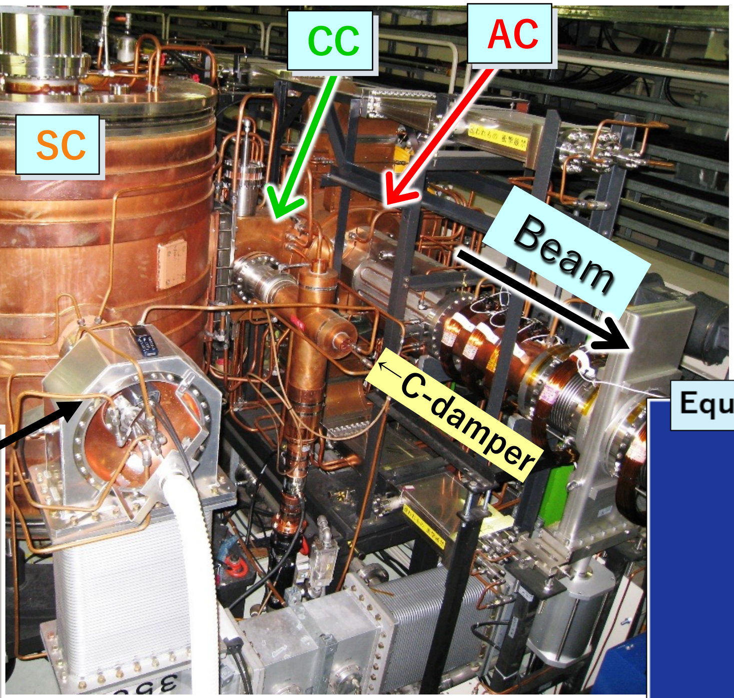
Resent operation status (2022ab, 4months)
# of Beam Aborts caused by RF system : 72
: 0.6 aborts/day
(Total # of beam aborts : >1300)

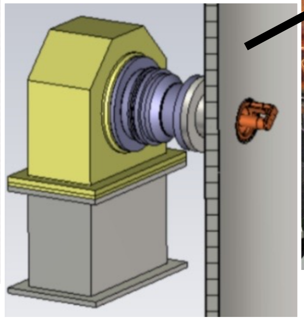
ARES : Accelerator Resonantly coupled to Energy Storage

T. Abe

Unique cavity specialized for KEKB

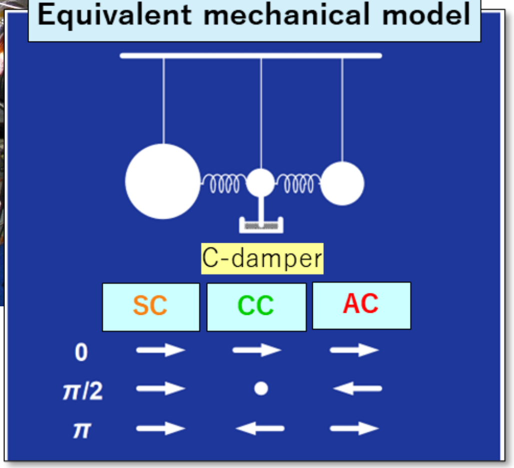






Parameters	
Freq.	509 MHz
R_{sh}/Q_0	15Ω
Q_0	~1.1x10^5
V_c (spec.)	0.5MV/cav.
P_{wall}	150kW

(60kW in AC, 90kW in SC)



- 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

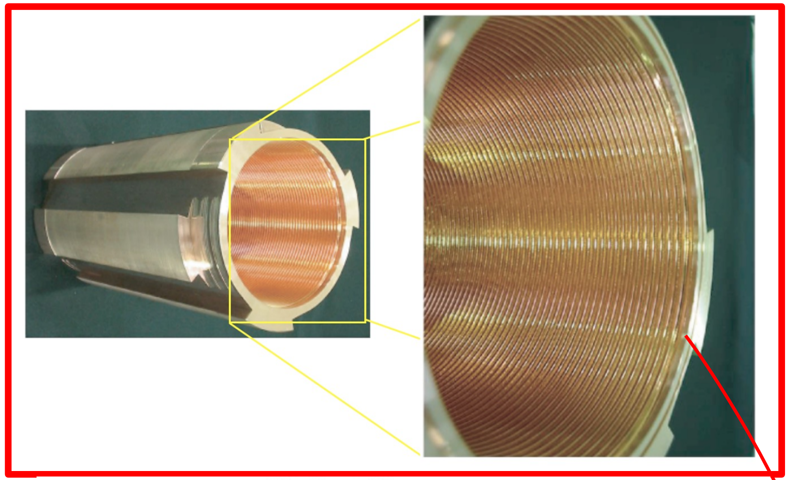
Upgrades of the high-power input coupler for SuperKEKB

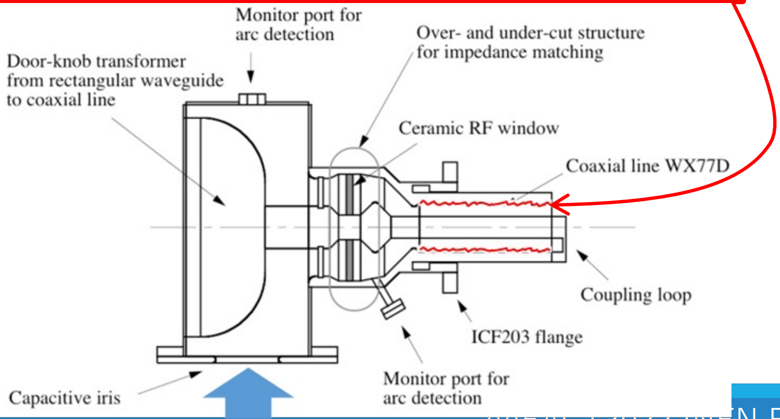
For the higher RF power (400 → 800kW max.) and higher beam currents (< 2A → 3.6A max.)

T. Abe

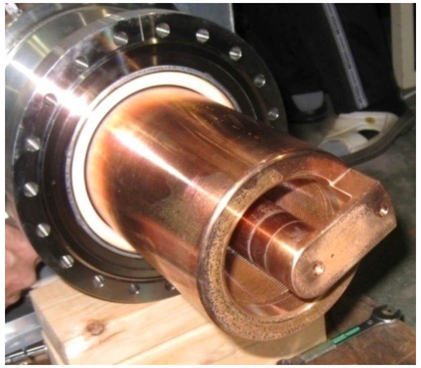
Fine grooving of the coaxial line to completely suppress multipactoring

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

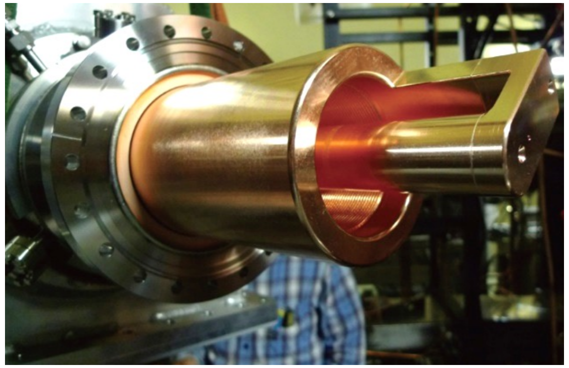




Increased input coupling (β_{max} = 3→6, β_{set} = 5) needed for the stations with the **Kly:Cav=1:1 configuration** to accelerate beams with the design current of LER



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

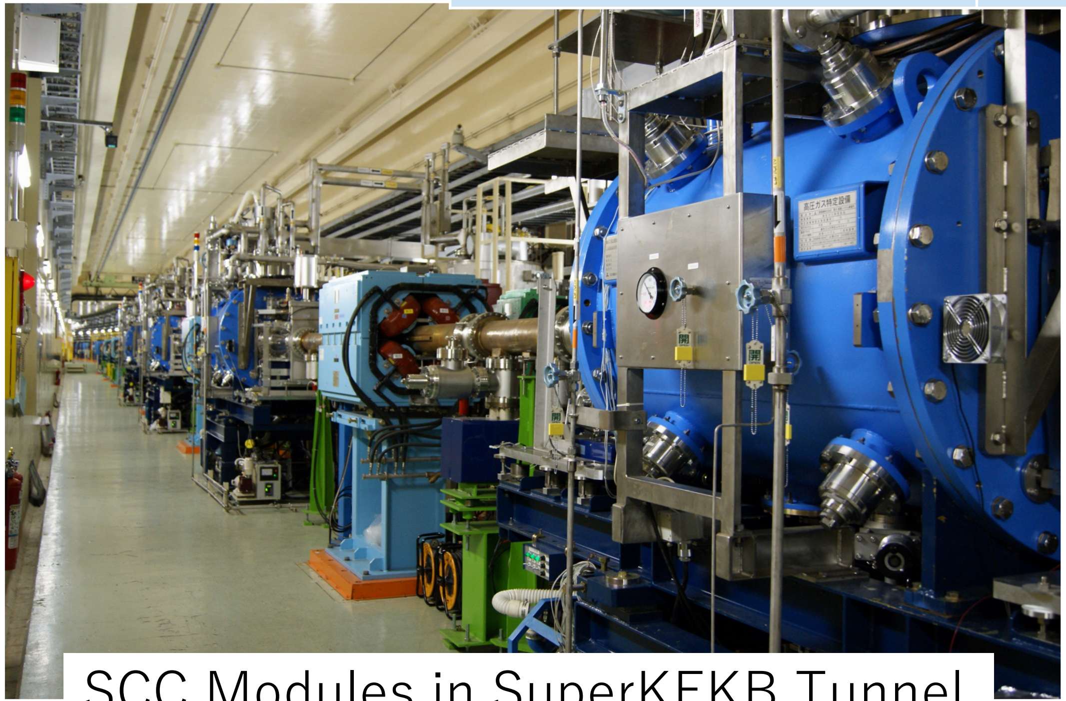
SCC

- 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**

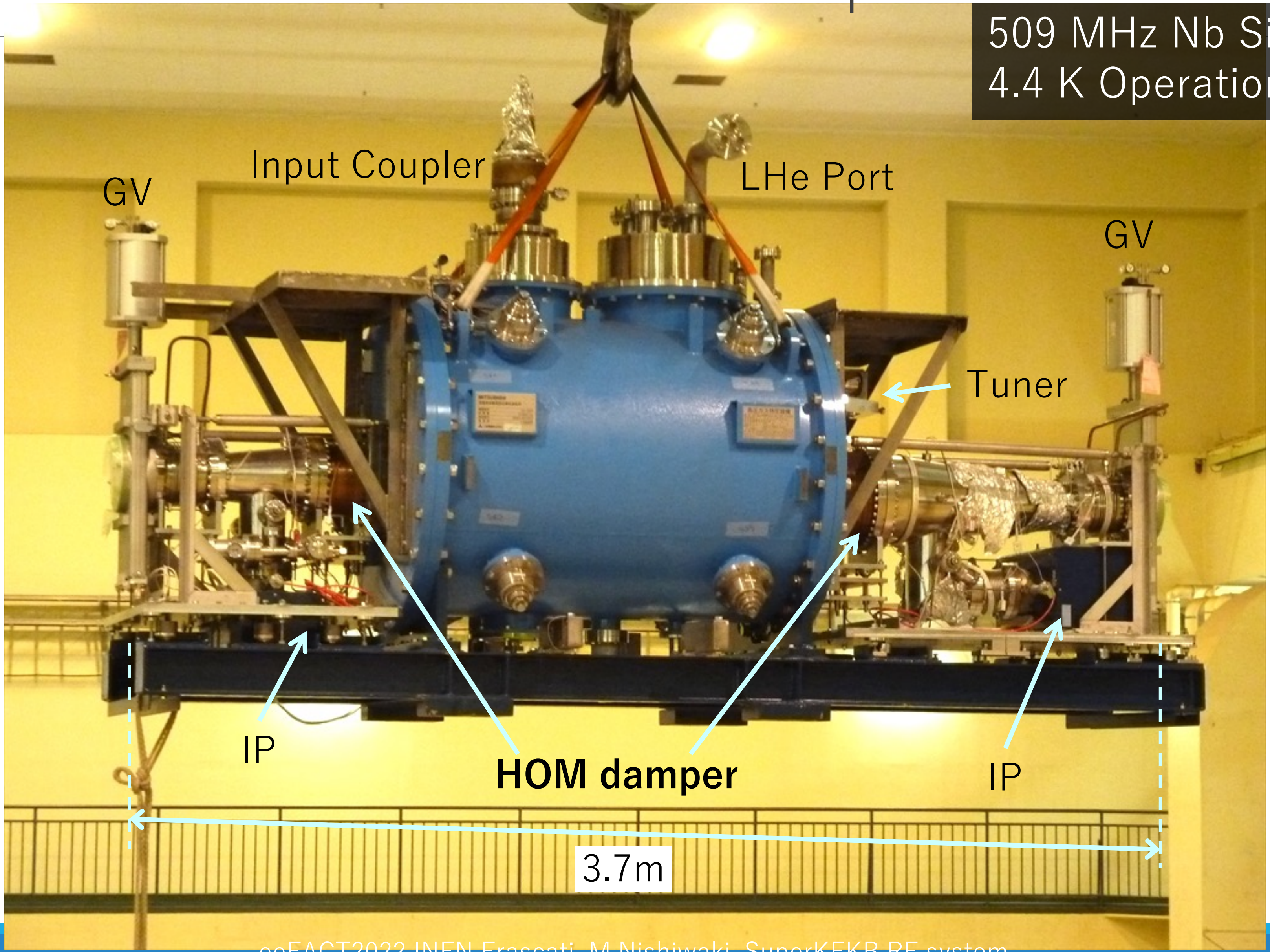
Resent Operation Status (Trip rate)

- 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

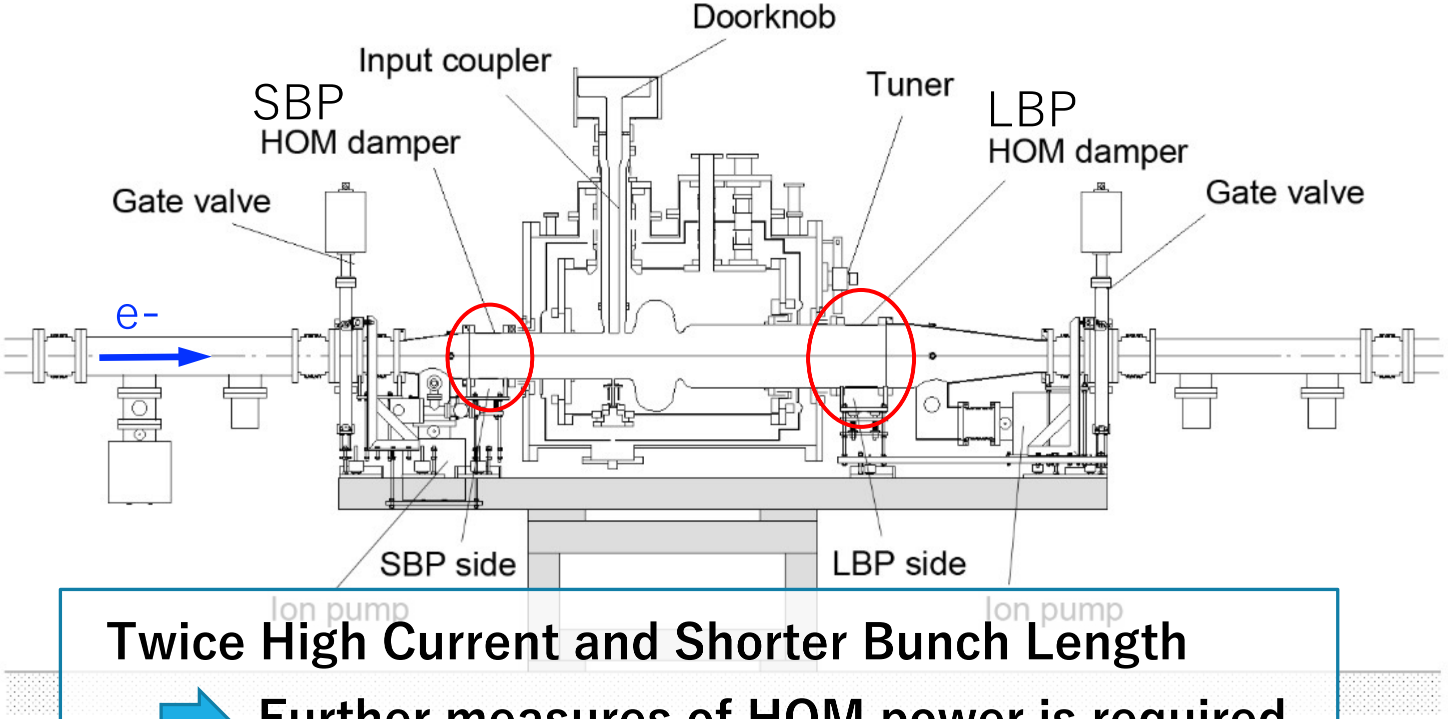
SCC Module of SuperKEKB

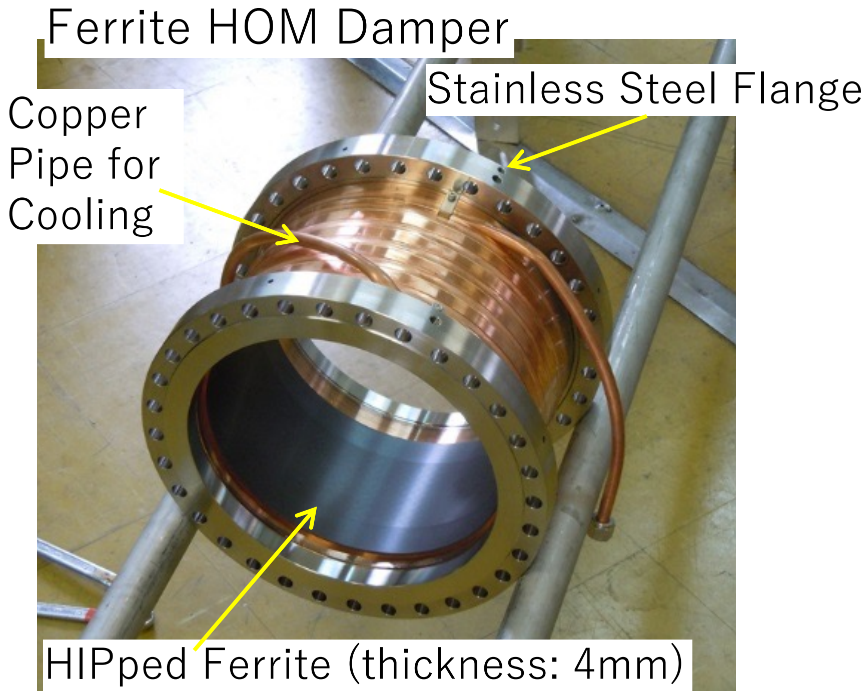


509 MHz Nb Single-cell Cavity
4.4 K Operation

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)





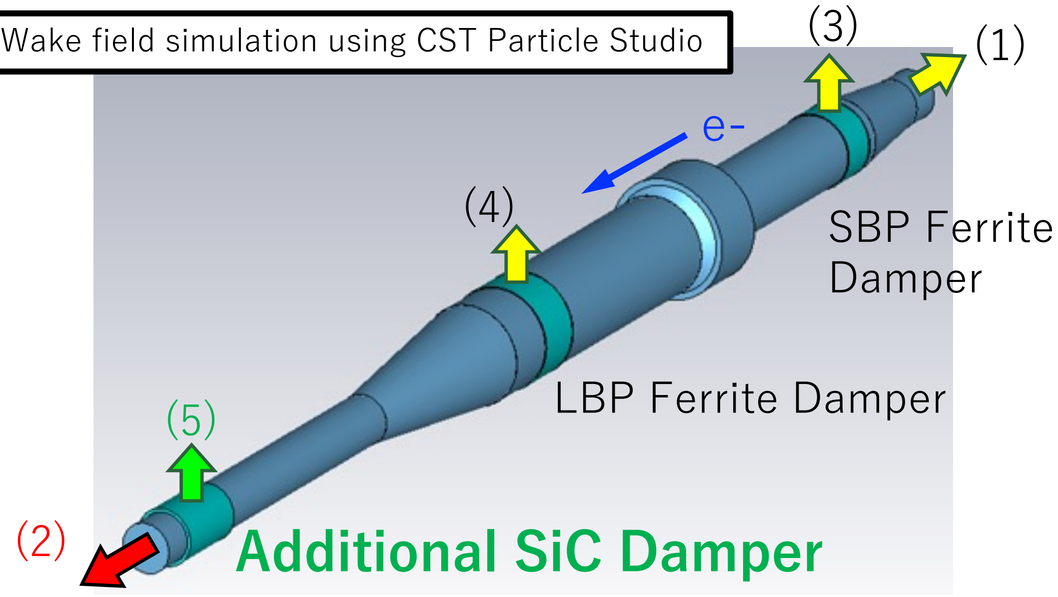
Twice High Current and Shorter Bunch Length

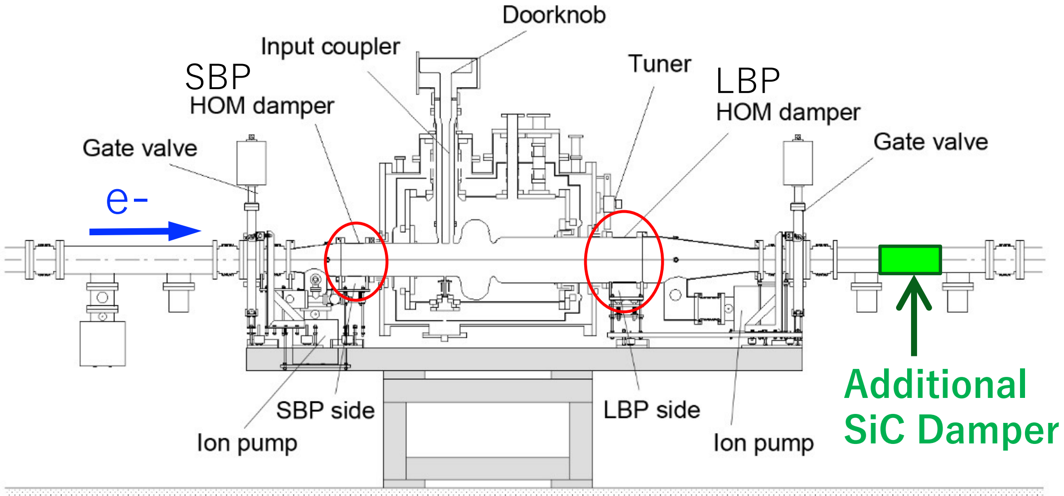
➡ **Further measures of HOM power is required.**

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

Estimation of HOM Power Flow

Wake field simulation using CST Particle Studio



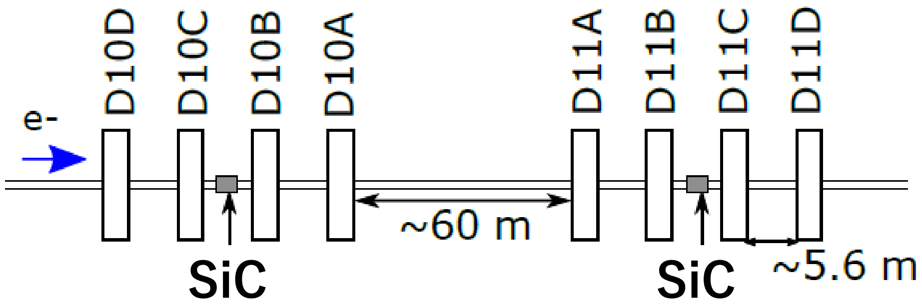


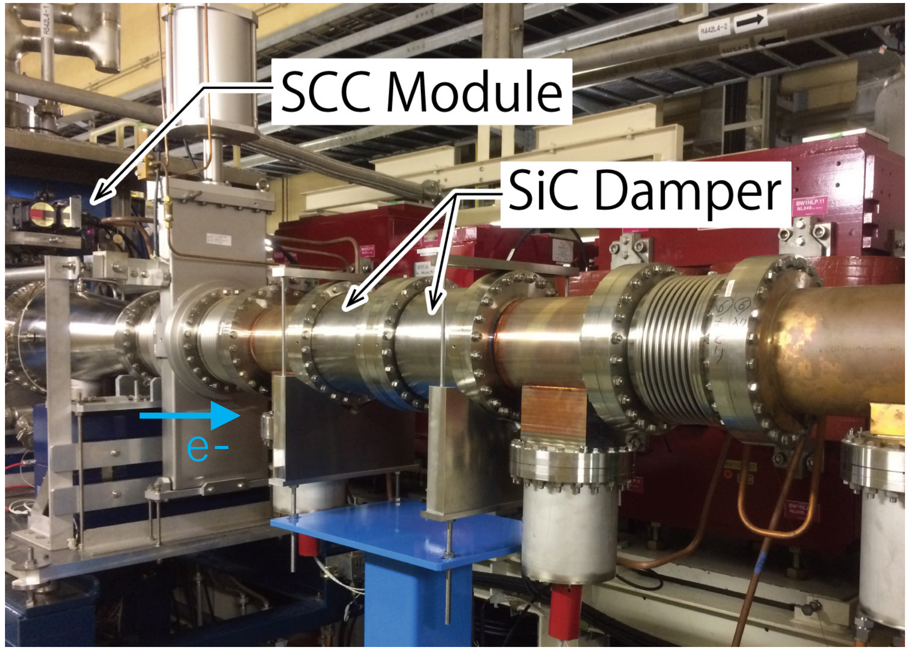
	Eq.LF [V/pC]	HOM Load @2.6A[kW]	Eq.LF [V/pC]	HOM Load @2.6A[kW]
(1) Emit into upstream	0.05	1.3	0.05	1.4
(2) Emit into downstream	0.58	15.7	0.15	4.0
(3) Abs. by SBP Ferrite	0.32	8.6	0.35	9.5
(4) Abs. by LBP Ferrite	0.43	11.7	0.47	12.8
Total	1.38	37.4	1.02	27.7
(5) Abs. by additional SiC	--	--	0.97	26.1

- 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.

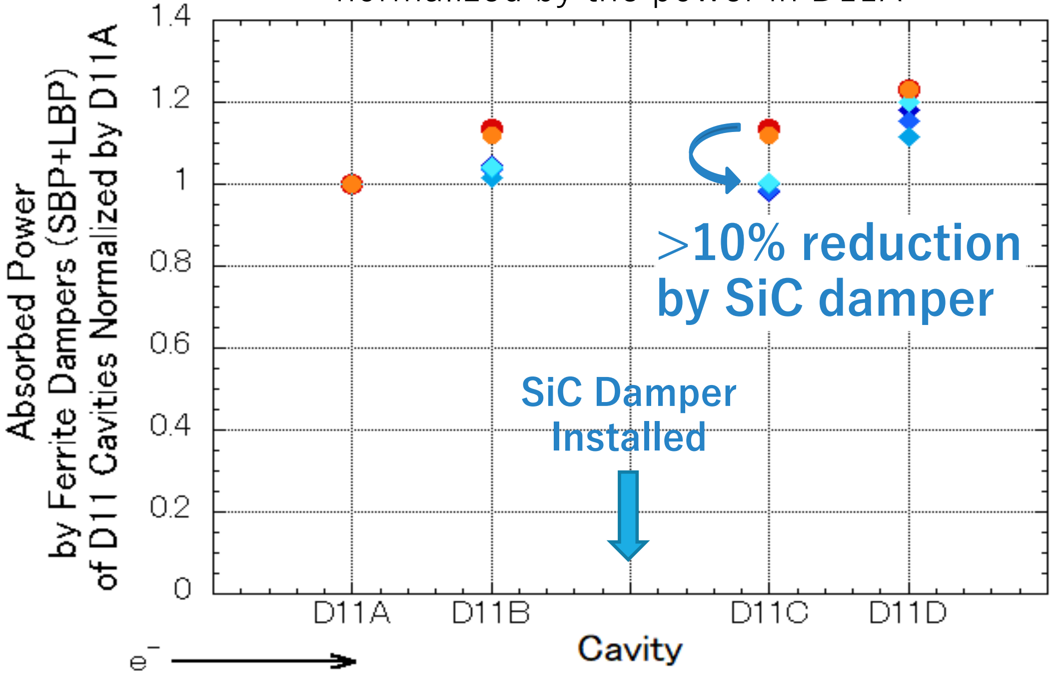
Results of Beam Test with SiC Damper

Layout of 8 SCCs and SiC dampers





Absorbed power by a pair of Ferrite dampers in D11 cavities normalized by the power in D11A



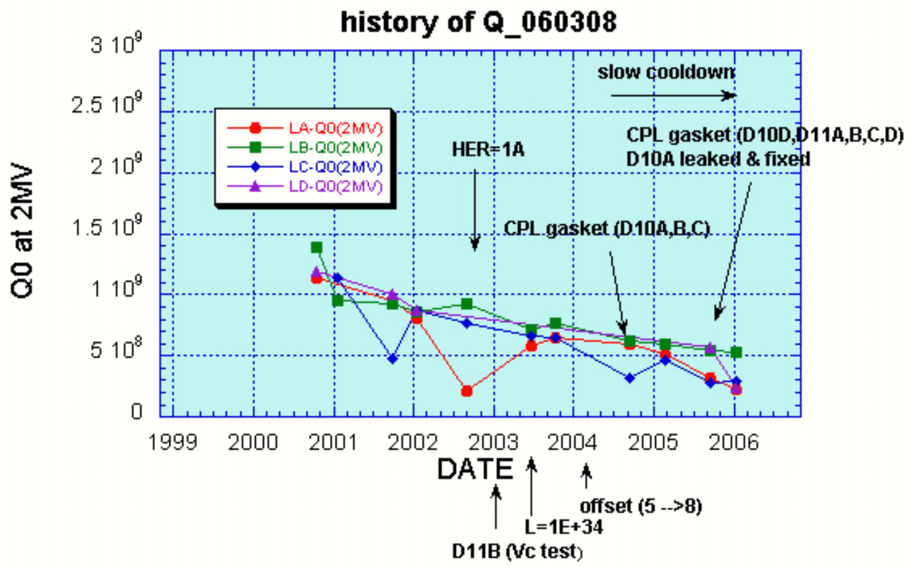
Absorbed HOM power at 1.1A (max. current) : ~ 8 kW/cavity

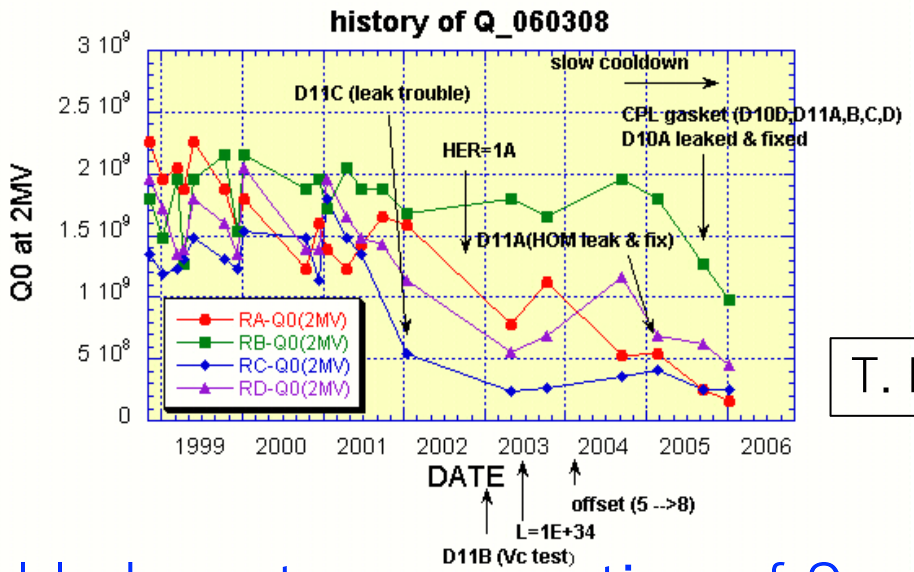
Two set of SiC dampers have been installed to SCC section for beam test. **The HOM power absorbed by the ferrite dampers of downstream cavities (D11C in plot) were reduced >10% after SiC damper installation.** It was confirmed that the additional SiC damper is effective to reduce the load of downstream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





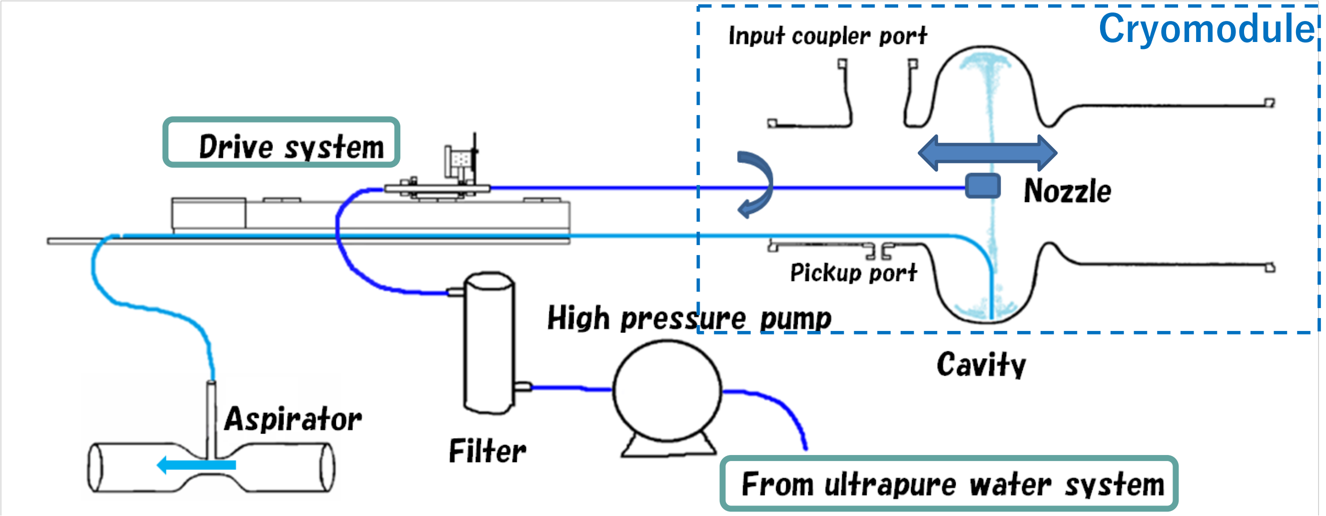
T. Furuya

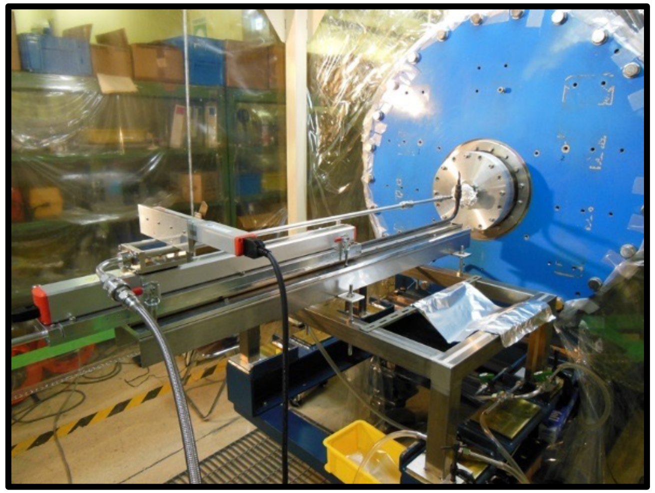
Performance recovery is desirable for stable long-term operation of SuperKEKB.

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.



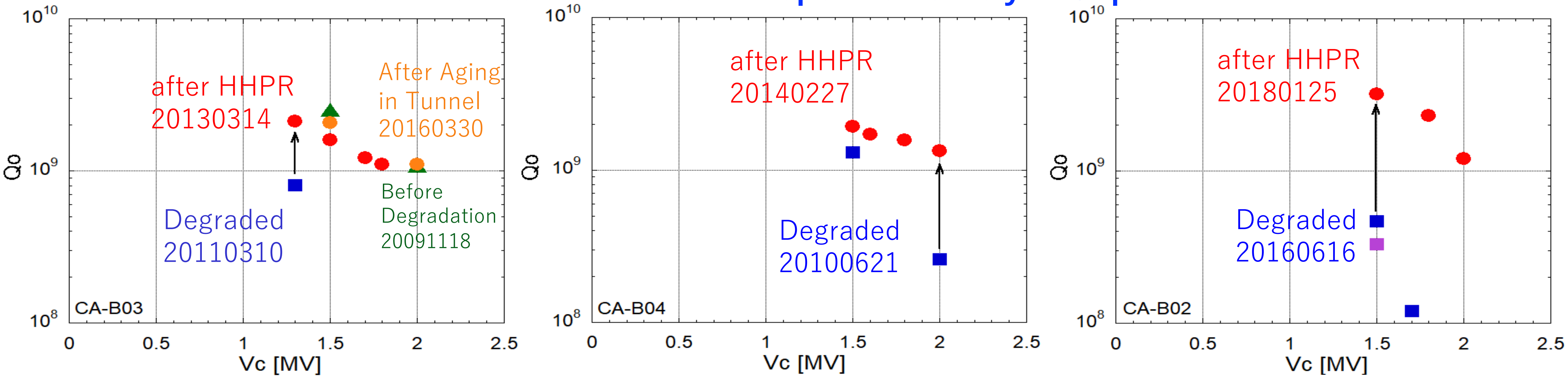


HHPR Parameters	
Water Pressure	7 MPa
Nozzle	ϕ0.54mm x 6
Driving speed	1 mm/sec.
Rotation speed	6 deg./sec.
Rinsing time	15 min.

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.**



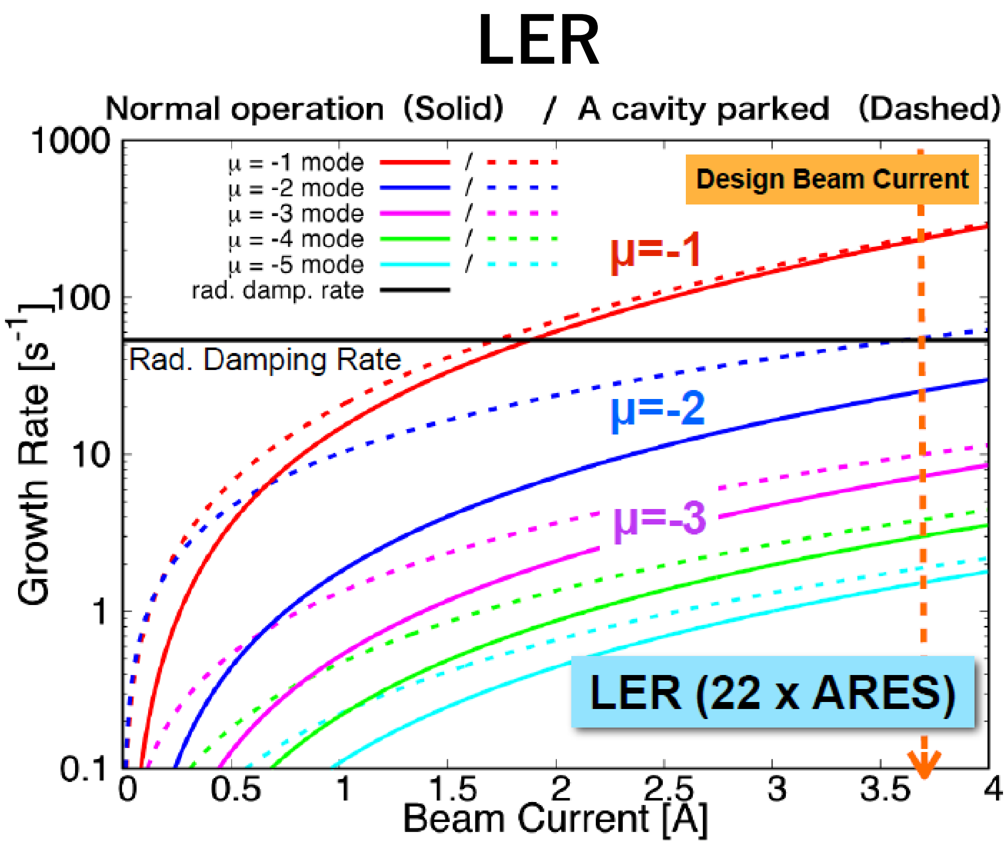
We are planning to perform the HHPR in the accelerator tunnel. There are many difficulties such as maintaining cleanliness, working in narrow spaces, and supplying ultrapure water. However, it has the great advantage that no extensive work is required to move the cavity out of the tunnel. We will continue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

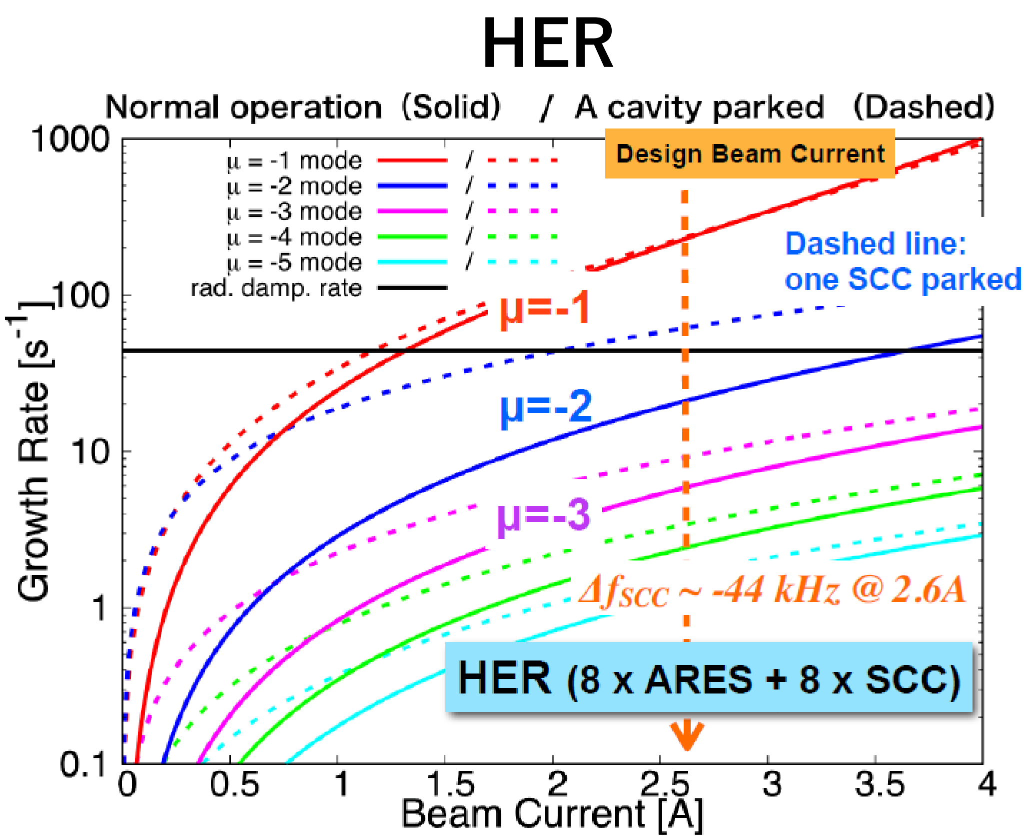
High Beam Current-related issues in RF system

- 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



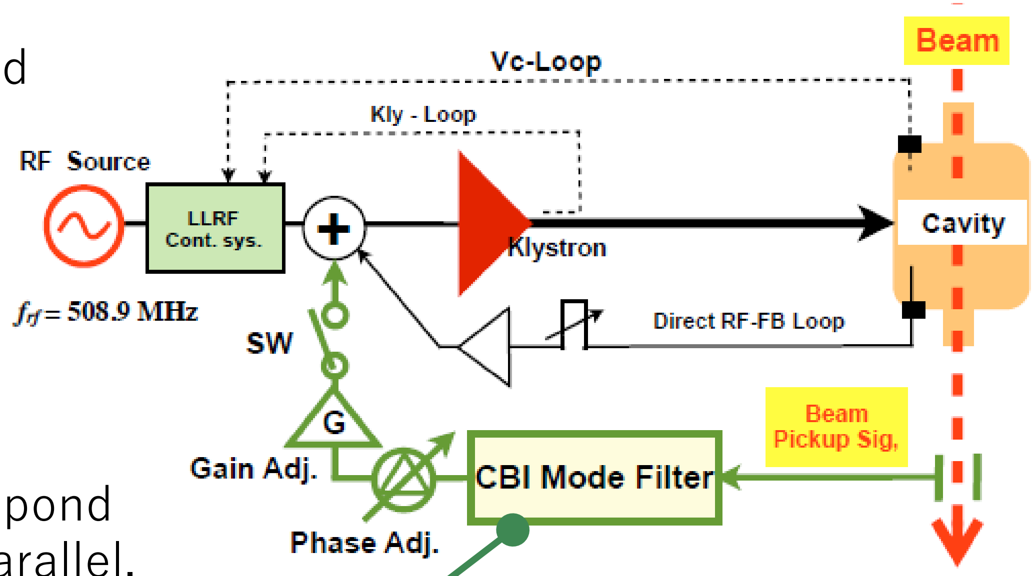


Threshold currents for μ=-1 mode are quite below the design current.
When there are parked cavities, μ=-2 mode also has no margin.
New CBI damper system has been developed and installed.

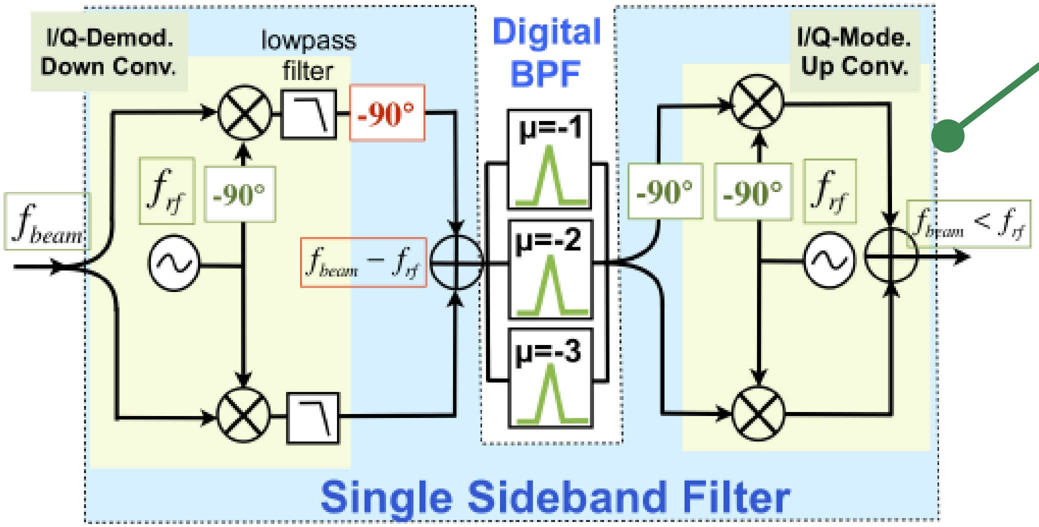
K. Hirosawa et al., Nucl. Instrum. Methods. Phys. Res. A 951, 163044, 2019.

CBI damper system

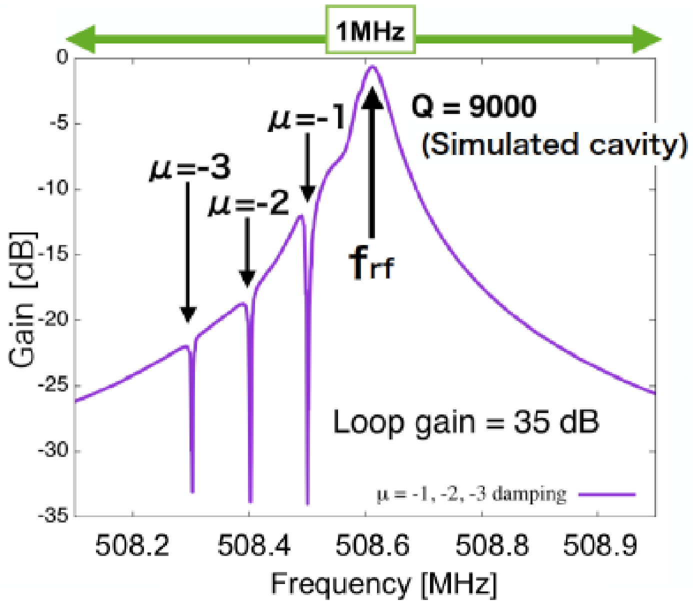
The damper system is installed to ARES station with digital LLRF system.



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



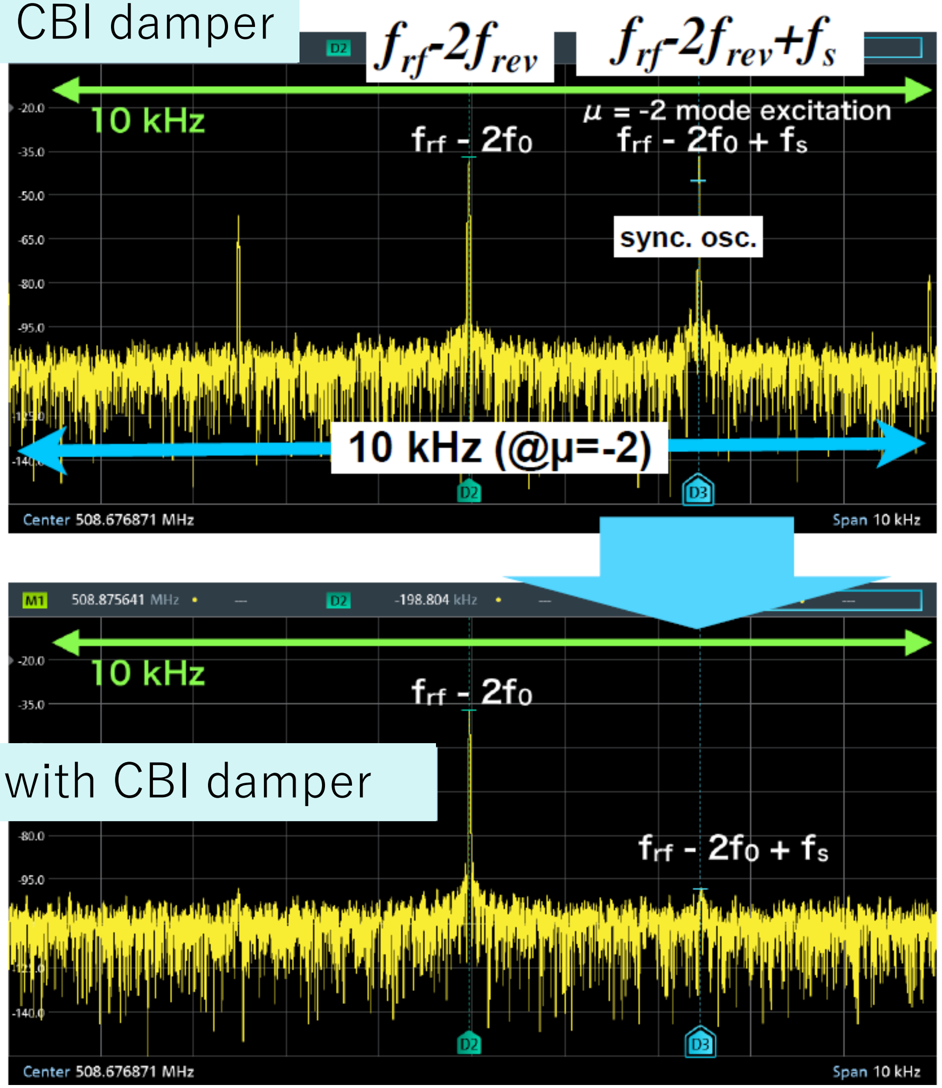
Frequencies correspond μ =-1, -2 and -3 modes are racked successfully.

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



with CBI damper

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

Peak disappeared by CBI damper.

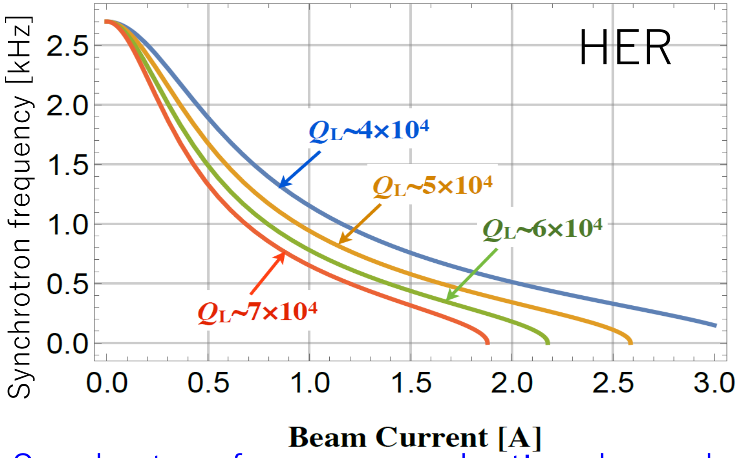
Up to 1.46 A for LER and 1.14 A for HER,
CBI is not a problem with this damper systems.

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

Zero-mode stability related to Robinson stability

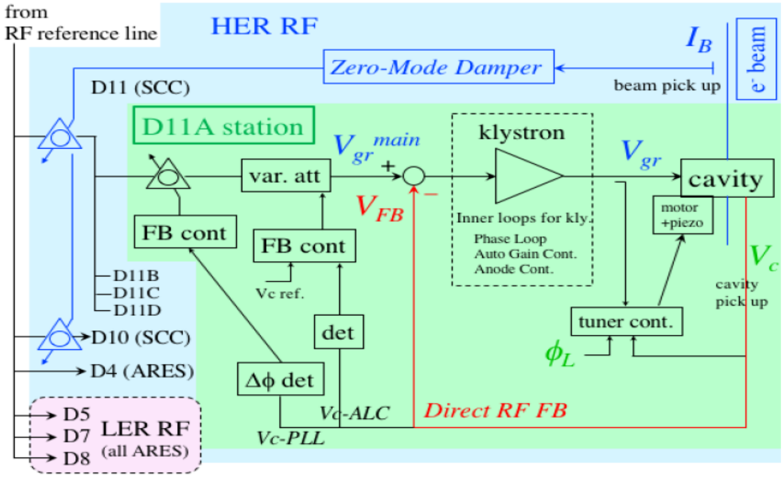
- In high current operation, synchrotron frequency reduction is expected due to coherent oscillation (zero-mode).
- To mitigate the beam-loading effect, Direct RF feedback (DRFB) and Zero-mode damper (ZMD) are working.

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



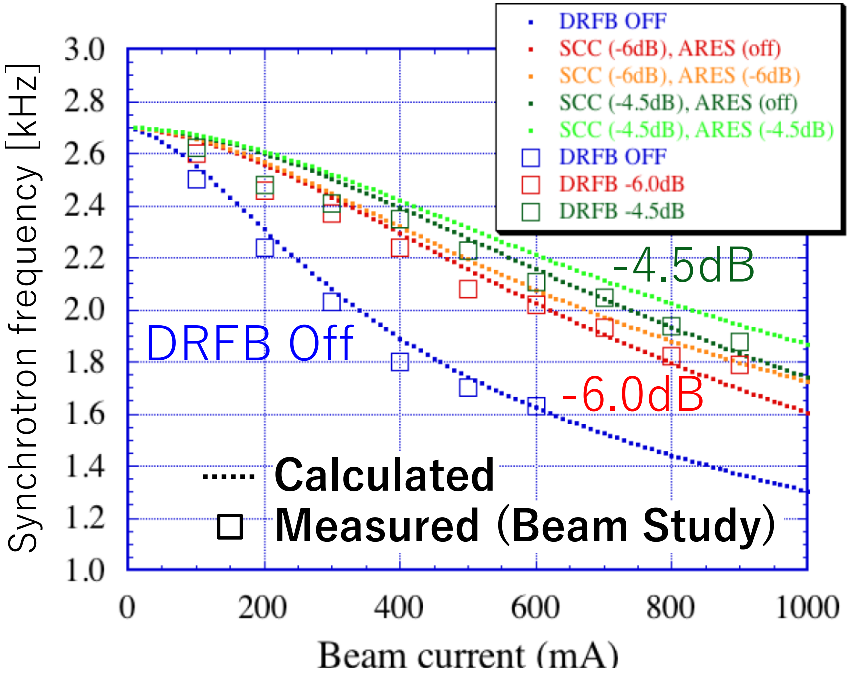
Synchrotron frequency reduction depends on Q_L. But, changing Q_L of SCC should be avoided due to the need for vacuum work and the risk of surface contamination.

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.

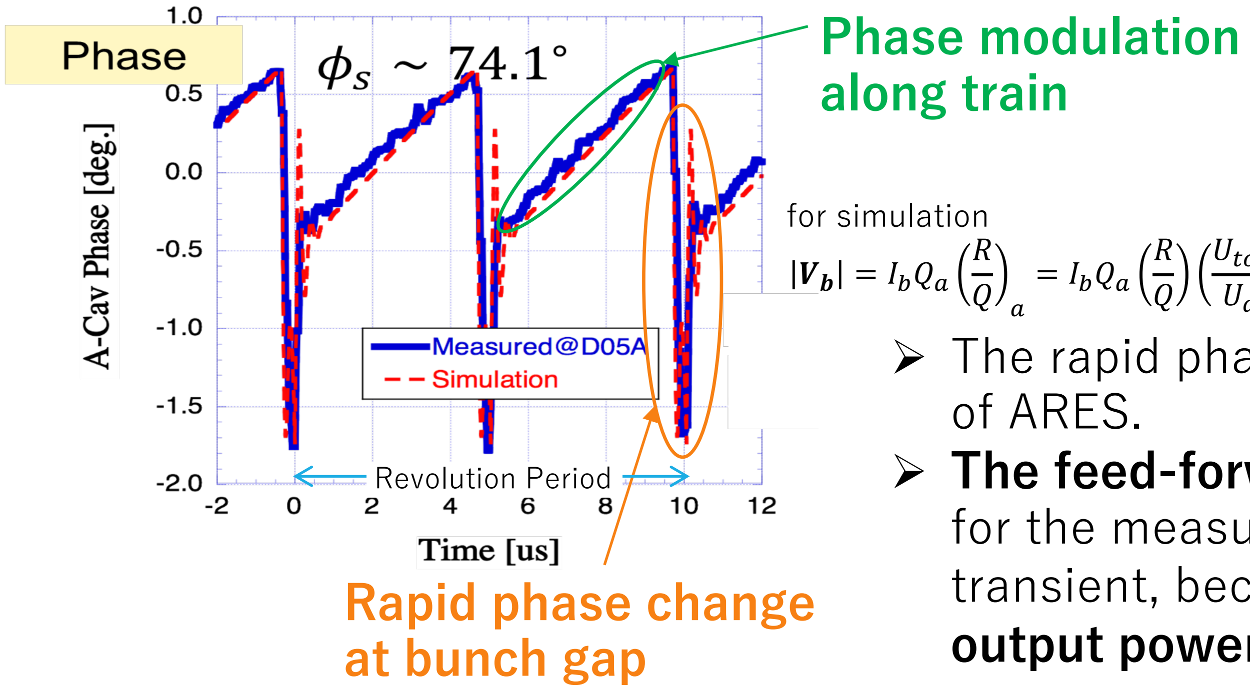
T.Kobayashi and K.Akai, Phys. Rev. Accel. Beams 19, 062001, 2016.

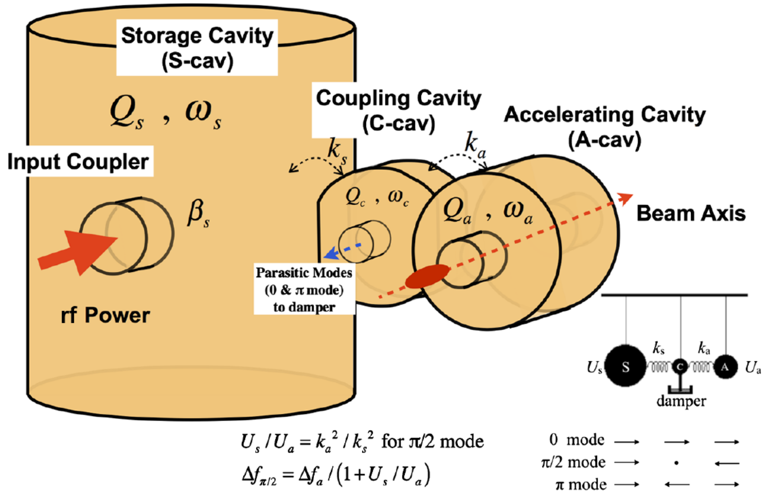
Calculation and measurement of Bunch Gap Transient

- 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)

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





for simulation

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

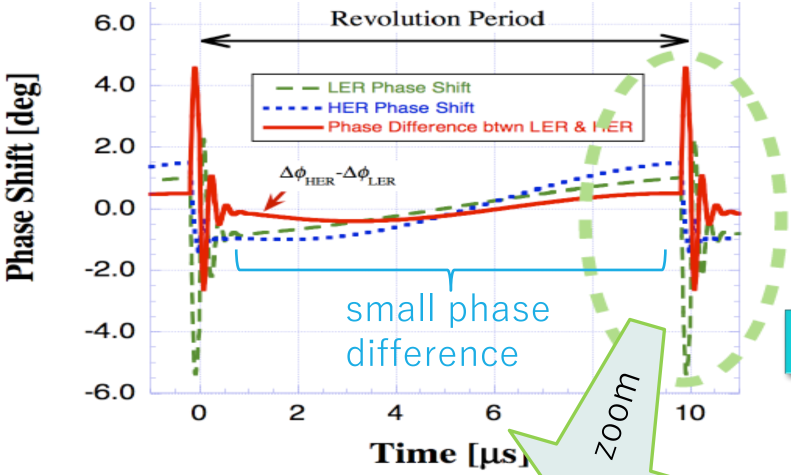
- The rapid phase change is attributed to the parasitic 0 and pi mode of ARES.
- **The feed-forward control cannot be available in our RF system** for the measures to reduce the phase modulation due to the gap transient, because the **klystron performance (bandwidth ~100kHz, output power) is not enough** to cancel the rapid phase modulation.

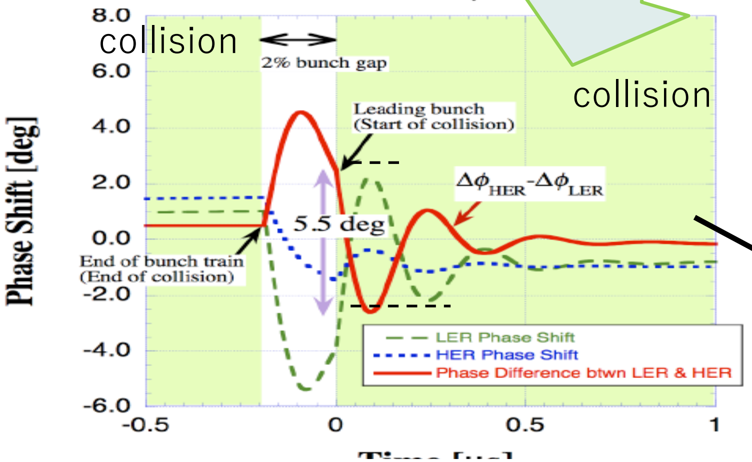
T.Kobayashi and K.Akai, Phys. Rev. Accel. Beams 19, 062001, 2016.

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

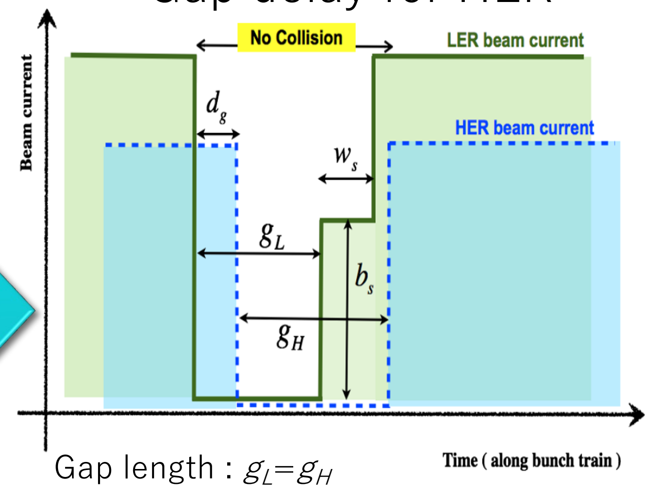




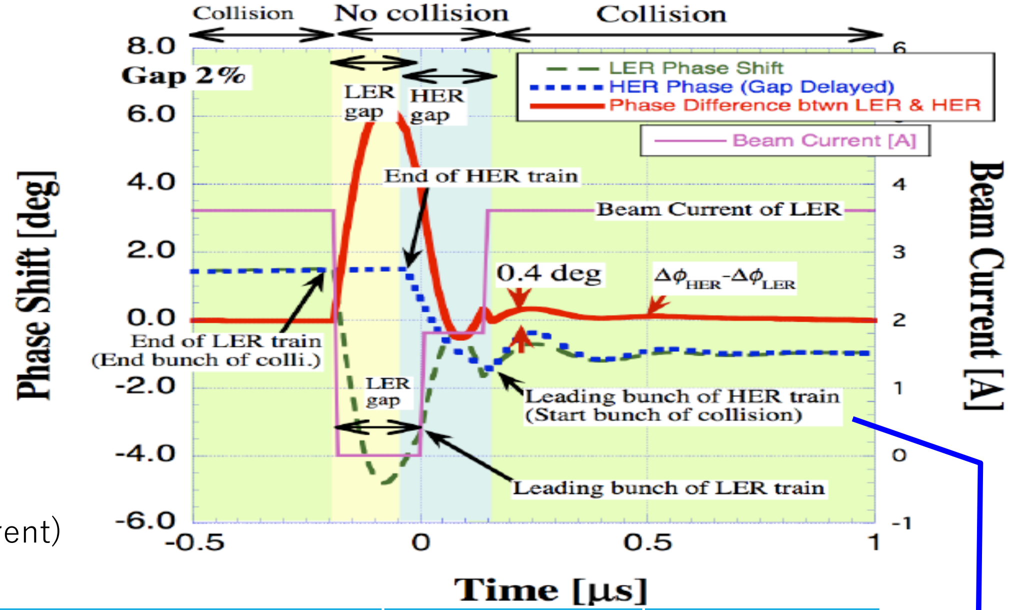
Large phase difference at leading part of collision

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!

Backup

Vc-Transient in 2021 operation

Working Status of RF System

File Edit Window 2021-12-17 11:23:54 Help

Station	Cav.	Status	Power	Vc	Set
D05	A	R HV R O RF SF IL FB	300.6 kW	0.412 MV	0.410 MV
	B	R HV R O RF SF IL FB	304.3 kW	0.409 MV	0.410 MV
	C	R HV R O RF SF IL FB	290.0 kW	0.410 MV	0.410 MV
	D	R HV R O RF SF IL FB	291.1 kW	0.410 MV	0.410 MV
	E	R HV R O RF SF IL FB	278.2 kW	0.410 MV	0.410 MV
	F	R HV R O RF SF IL FB	278.3 kW	0.410 MV	0.410 MV
D07	A	R HV R O RF SF IL FB	512.3 kW	0.849 MV	0.840 MV
	B	R HV R O RF SF IL FB	452.3 kW	0.856 MV	0.840 MV
	C	R HV R O RF SF IL FB	306.3 kW	0.419 MV	0.420 MV
	D	R HV R O RF SF IL FB	278.9 kW	0.424 MV	0.420 MV
	E	R HV R O RF SF IL FB	418.3 kW	0.850 MV	0.840 MV
D08	A	R HV R O RF SF IL FB	456.9 kW	0.842 MV	0.840 MV
	B	R HV R O RF SF IL FB	517.0 kW	0.848 MV	0.840 MV
	C	R HV R O RF SF IL FB	274.5 kW	0.421 MV	0.420 MV
	D	R HV R O RF SF IL FB	200.7 kW	0.403 MV	0.400 MV
	E	R HV R O RF SF IL FB	371.4 kW	0.801 MV	0.800 MV
D04	A	R HV R O RF SF IL FB	483.7 kW	0.801 MV	0.800 MV
	C	R HV R O RF SF IL FB	517.1 kW	0.801 MV	0.800 MV
	E	R HV R O RF SF IL FB	275.5 kW	0.457 MV	0.450 MV
	F	R HV R O RF SF IL FB	353.3 kW	0.450 MV	0.450 MV
	G	R HV R O RF SF IL FB	299.8 kW	0.451 MV	0.450 MV
	H	R HV R O RF SF IL FB	356.5 kW	0.450 MV	0.450 MV
D10	A	R HV R O RF SF IL FB	213.8 kW	1.349 MV	1.350 MV
	B	R HV R O RF SF IL FB	192.1 kW	1.349 MV	1.350 MV
	C	R HV R O RF SF IL FB	188.8 kW	1.355 MV	1.350 MV
	D	R HV R O RF SF IL FB	199.8 kW	1.348 MV	1.350 MV
D11	A	R HV R O RF SF IL FB	216.1 kW	1.353 MV	1.350 MV
	B	R HV R O RF SF IL FB	215.7 kW	1.352 MV	1.350 MV
	C	R HV R O RF SF IL FB	207.8 kW	1.356 MV	1.350 MV
	D	R HV R O RF SF IL FB	192.0 kW	1.347 MV	1.350 MV
DR	A	R HV R O RF SF IL FB	127.1 kW	1.000 MV	1.000 MV

LER Vc 9.177 MV
Beam 1000.2 mA

HER Vc 14.234 MV
Beam 800.2 mA

DR Vc 1.000 MV
Beam 14.2 mA

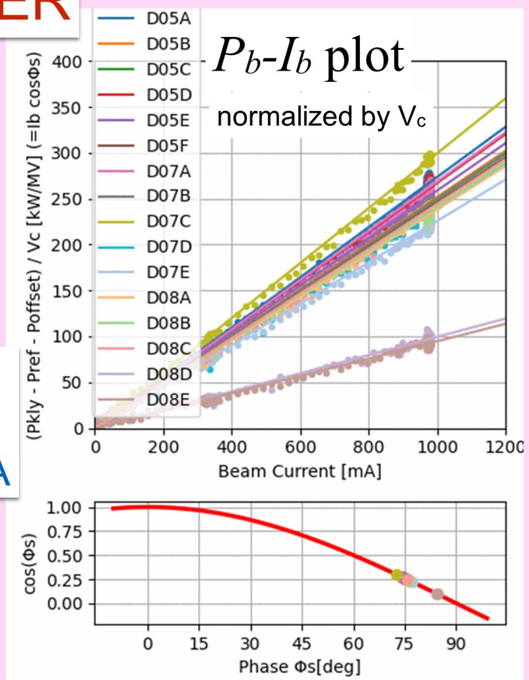
SKBRFDisplayCATV on localhost:41.0

LER: 1A,
HER: 800mA

Beam Loading (Op. Conditions)

$$P_b = I_b V_c \cos\phi_s$$
$$= P_{kly} - P_r - P_c$$

LER

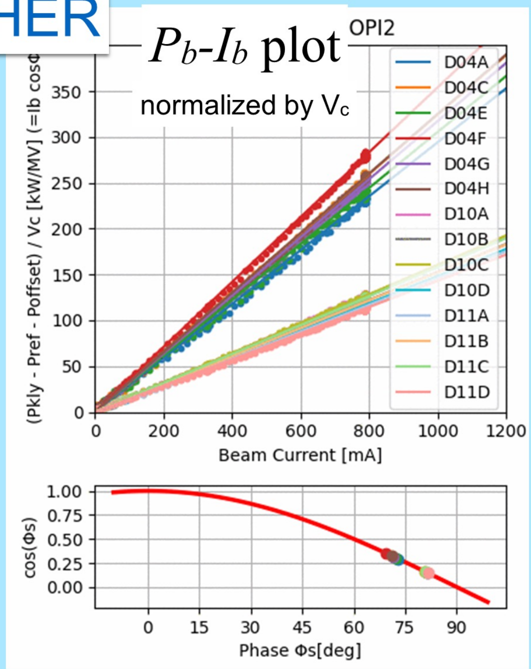


ARES (D05A)

$\phi_s \sim 74.1°$

$\Delta f_{opt} \sim -89.5$[kHz]
(for A-cav)

HER



ARES (D04F)

$\phi_s \sim 69.3°$ $\Delta f_{opt} \sim -63.5$[kHz]
(for A-cav)

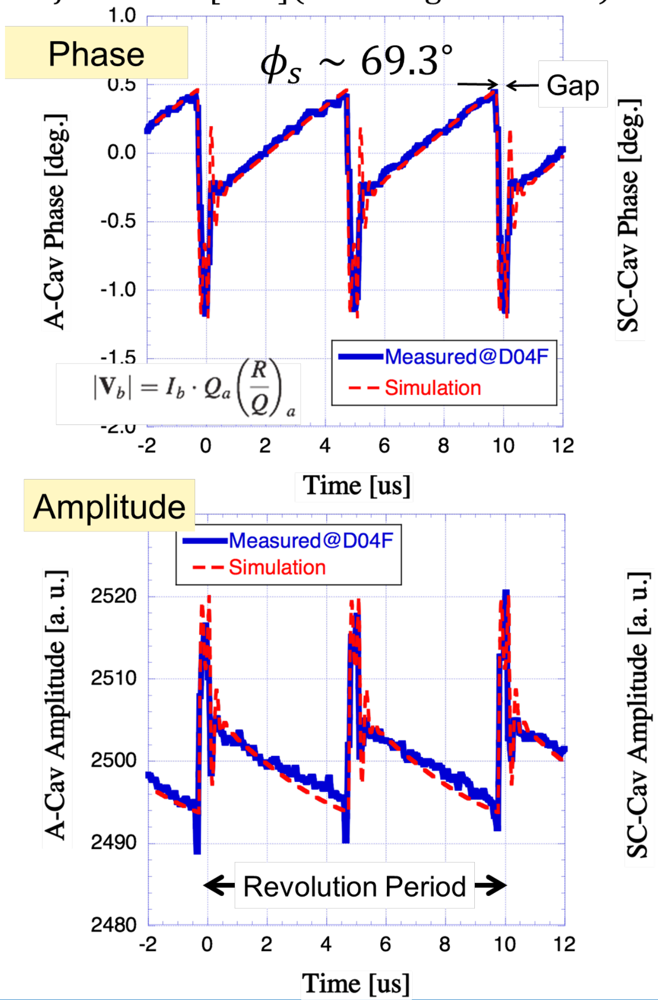
SCC

$\phi_s \sim 81.3°$ $\Delta f_{opt} \sim -13.9$[kHz]

Vc-Transient with Two Bunch Gap in HER

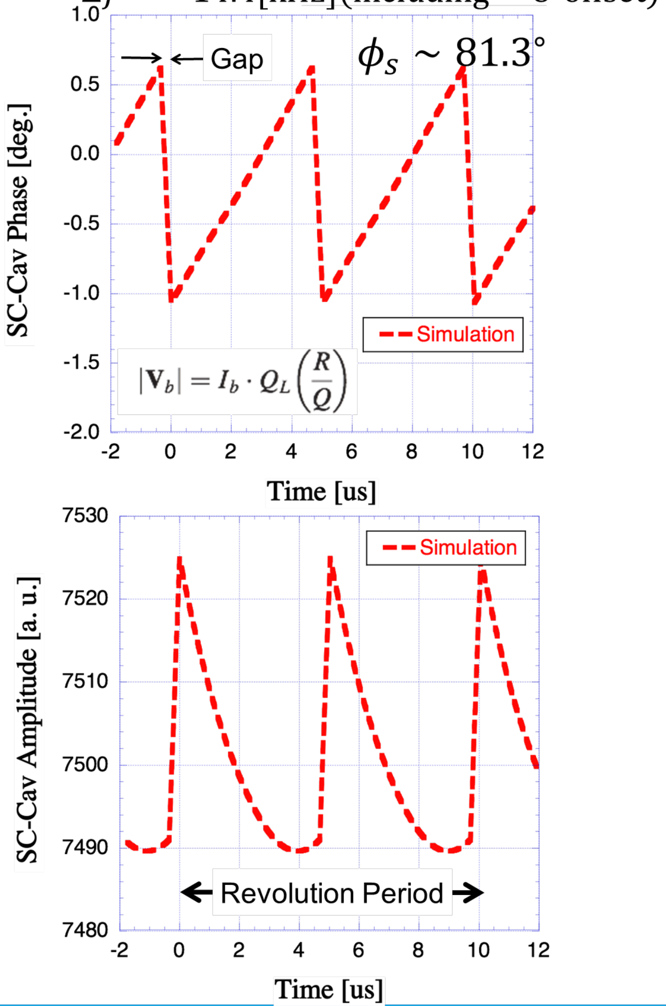
HER ARES (D04F)

$\Delta f \sim -74.5[\text{kHz}](\text{including} - 5^\circ\text{offset})$



HER SCC Vc (only simulation)

$\Delta f \sim -14.4[\text{kHz}](\text{including} - 8^\circ\text{offset})$

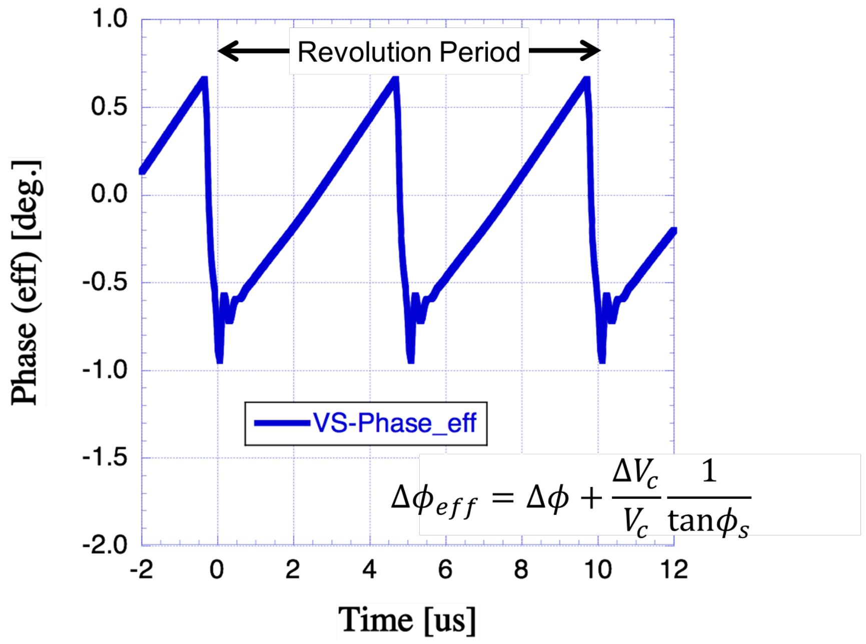


Beam Curren : 800mA

Vector Sum of SCC & ARES from simulation data

SCC(Vc=1.35MV) x 8 + ARES (Vc=0.45) x 8
with 10-deg phase difference between SCC&ARES

Assuming that all cavities are operated with the same condition for SCC and ARES, respectively



$$\Delta\phi_{eff} = \Delta\phi + \frac{\Delta V_c}{V_c}\frac{1}{\tan\phi_s}$$

Plot shows the effective phase including Vc-change for beam phase.

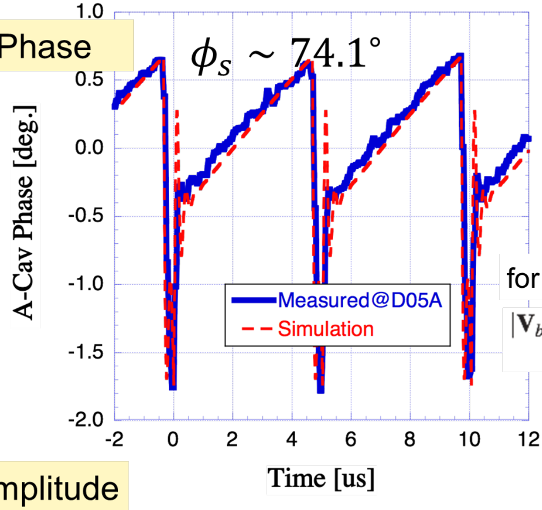
Vc-Transient in LER & Comparison with HER

LER ARES (D05A)

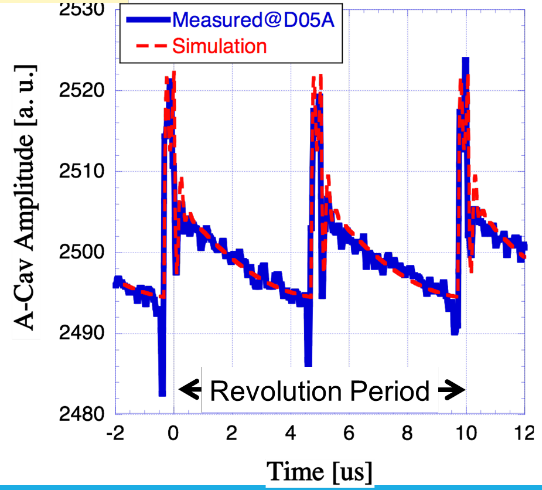
Beam Current 1A

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

Phase



Amplitude

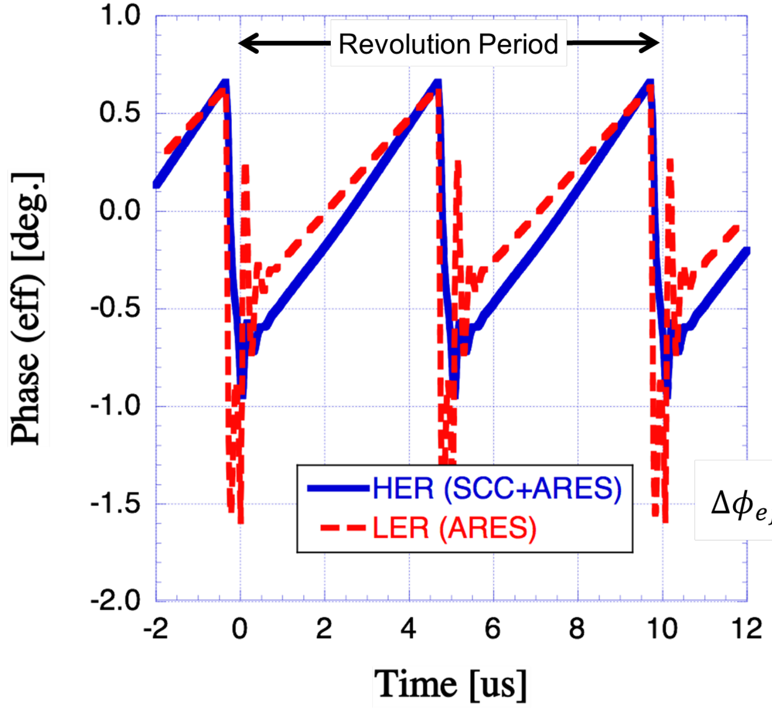


for simulation

$$|\mathbf{V}_b| = I_b \cdot Q_a \left(\frac{R}{Q}\right)_a = I_b \cdot Q_a \left(\frac{R}{Q}\right)\left(\frac{U_{\text{tot}}}{U_a}\right)$$

Superposition Plot of LER & HER (Vector-Sum) for the Simulation Data

Assuming that all ARES's are operated with the same condition in LER

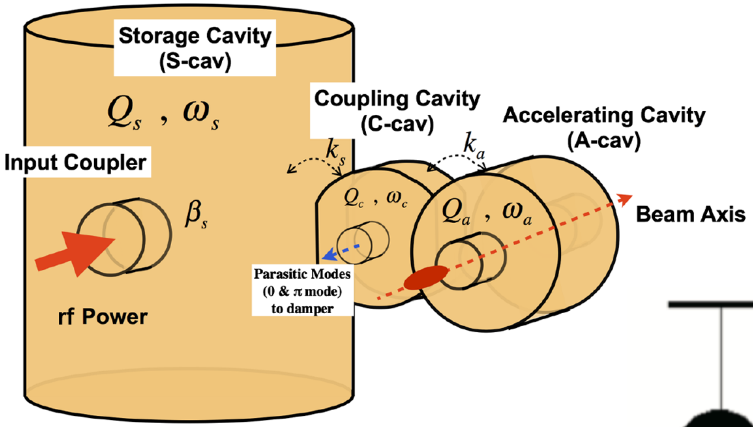


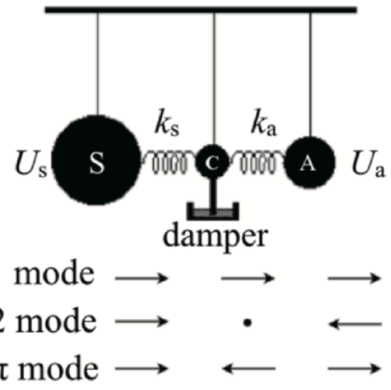
$$\Delta\phi_{eff} = \Delta\phi + \frac{\Delta V_c}{V_c}\frac{1}{\tan\phi_s}$$

Phase difference between HER & LER is about 0.5 ~ 1deg. at the leading part of the train (depending on the collision offset)

ARES

ARES in SuperKEKB Tunnel





$U_s/U_a = k_a^2/k_s^2$ for π/2 mode

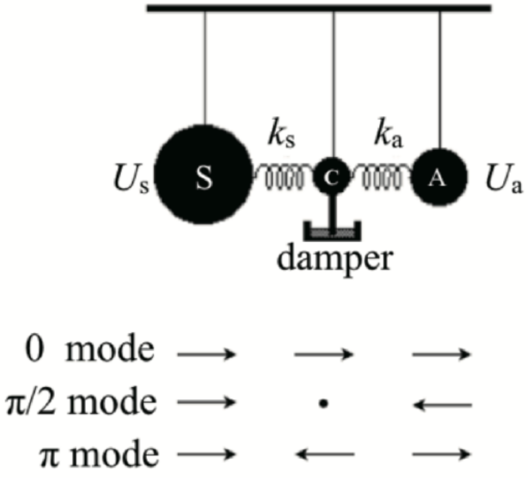
$\Delta f_{\pi/2} = \Delta f_a / (1 + U_s/U_a)$

- Unique cavity specialized for KEKB
- Consist of a three-cavity system operated in the π/2 mode
- Accelerating (A-) cavity is coupled to a storage (S-) cavity via a coupling (C-) cavity.
- The A-cavity is structured to damp HOM.
- The C-cavity is equipped with a damper to damp parasitic 0- and π-modes.

ARES

Key features of the ARES scheme based on the $\pi/2$ -mode resonant coupling are summarized as follows.

- The stored energy ratio for the $\pi/2$ mode is given by $U_s/U_a = k_a^2/k_s^2$, where U_a is the stored energy in the A-cavity and U_s is the energy in the S-cavity, k_a is the coupling factor between the A- and C-cavities and k_s the coupling factor between the S- and C-cavities.



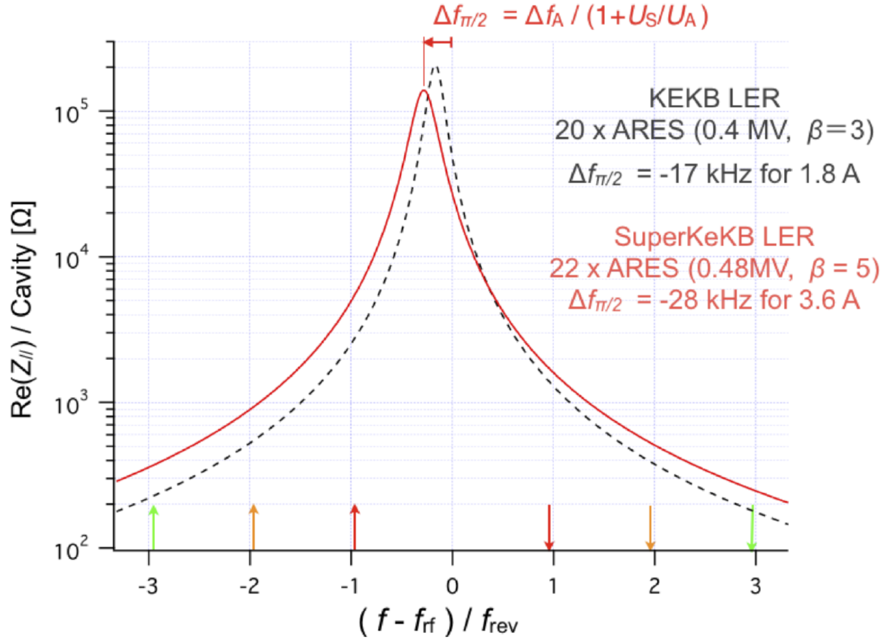
$U_s/U_a = k_a^2/k_s^2$ for $\pi/2$ mode

$\Delta f_{\pi/2} = \Delta f_a / (1 + U_s/U_a)$

- The $\pi/2$ mode shows extraordinary field stability, which assures that the stored energy ratio U_s/U_a can be kept almost constant in the presence of detuning by Δf_a for the A-cavity loaded with beam. Therefore, the detuning of the $\pi/2$ mode will be reduced as $\Delta f_{\pi/2} = \Delta f_a/(1 + U_s/U_a)$. (In ARES, $U_s/U_a = 9$, then $\Delta f_{\pi/2} = \Delta f_a/10 \sim 30kHz$.)
- The parasitic 0 and π modes can be selectively damped by equipping the C-cavity with a damper.
- Moreover, the damped 0 and π modes are nearly symmetrically located with respect to the RF frequency. Therefore, the impedance contributions from these two modes to CBIs cancel each other out to some extent.

ARES

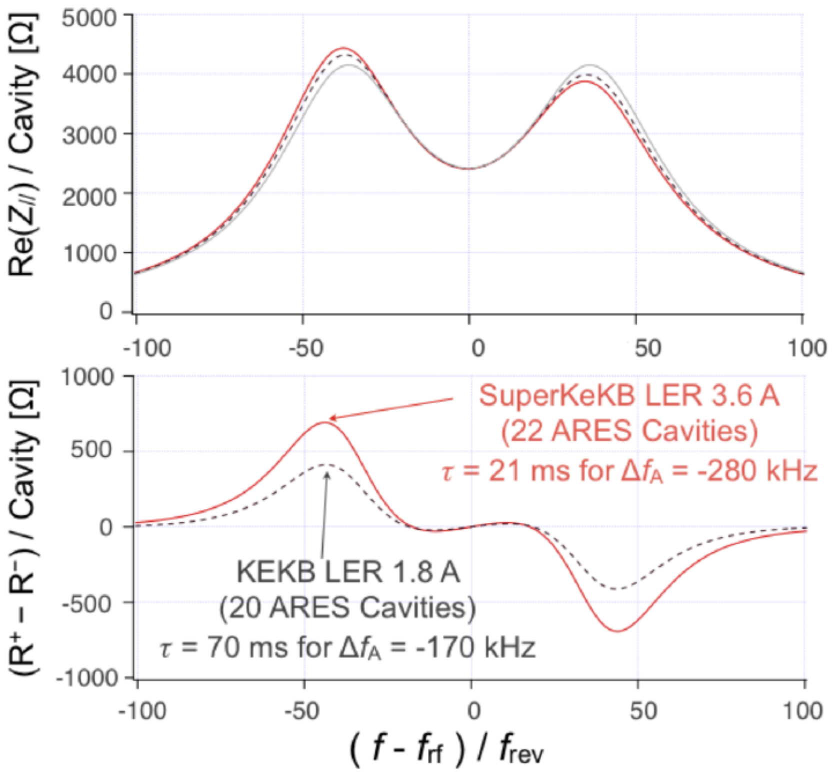
Coupling impedance of the $\pi/2$ mode calculated for the SuperKEKB compared with that for the KEKB



- The amount of frequency detuning $\Delta f_{\pi/2} = \Delta f_a/(1 + U_s/U_a)$ for the $\pi/2$ mode increases from 17 kHz to 28 kHz, however, still being kept below 1/3 of the beam revolution frequency of 99.4 kHz.
- The impedance spectrum becomes broad since the coupling factor β being increased from 3 to 5.

ARES

Coupling impedance (top) of the 0 and π modes, and the imbalance (bottom) with respect to the RF frequency



The 0 and π modes are located nearly mirror-symmetrically with respect to the π/2 mode to be tuned into the vicinity of the RF frequency. Therefore, the impedance contributions from the damped 0- and π-mode resonances to CBI can be counterbalanced between excitation and damping.

However, detuning of the accelerating cavity by Δf_a affects the field distributions of the 0 and π modes in the first order. The impedance imbalance (the difference between the original waveform and its mirror image obtained by horizontal reverse with respect to the RF frequency) is also shown, where excitation is positive and damping is negative, and the fastest growth time is indicated for each case. As for the KEKB LER, the fastest growth time is estimated 70 ms at a beam current of 1.8 A, much slower than the radiation damping time of 21 ms. As for the SuperKEKB LER with the design beam current of 3.6 A, the fastest growth time is estimated 21 ms for a CBI mode number around -40, that is about -4 MHz apart from the RF frequency. It is slightly faster than the radiation damping time of 22 ms, however, slow enough for a longitudinal bunch-by-bunch feedback system to cure.

ARES

T.Abe, ALERT2014 Workshop

Appendix A (3/5)

Longitudinal CBI driven by the parasitic 0 and π modes

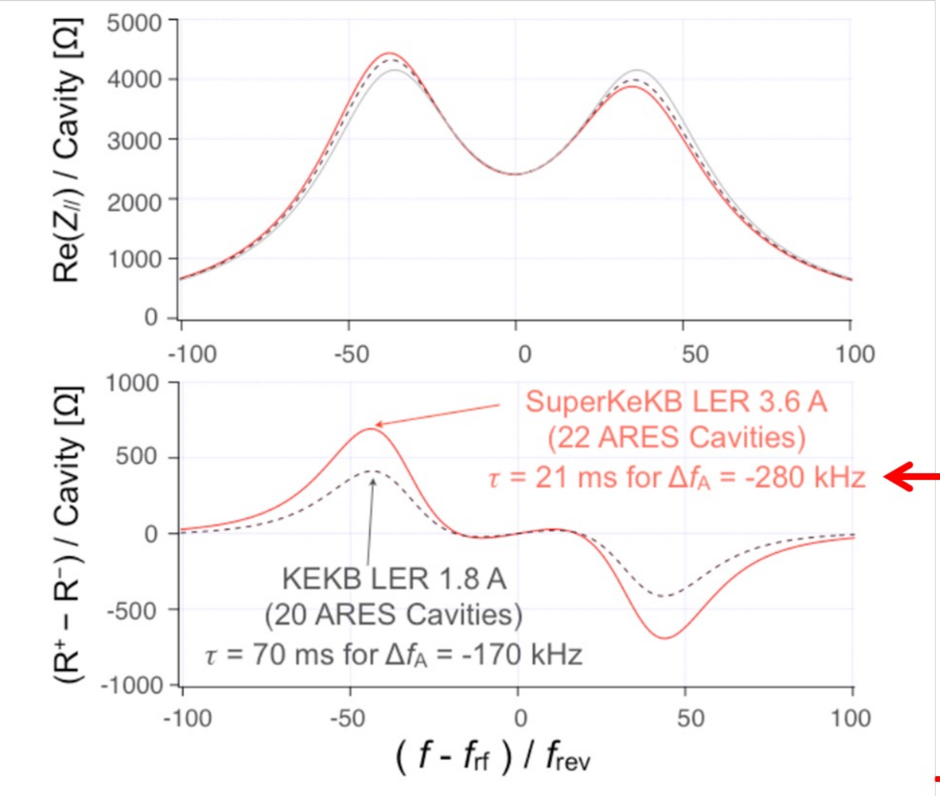
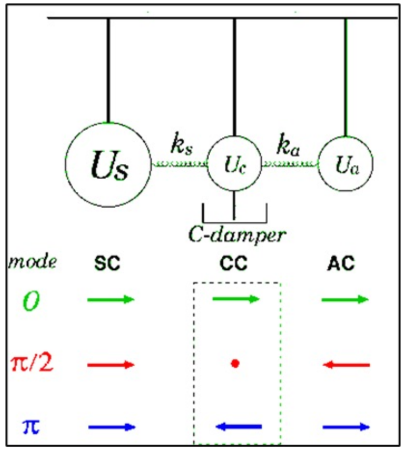


Figure 7.10: Coupling impedance (top) of the 0 and π modes, and the imbalance (bottom) with respect to the RF frequency.



To be cured by the longitudinal bunch-by-bunch feedback system

ARES

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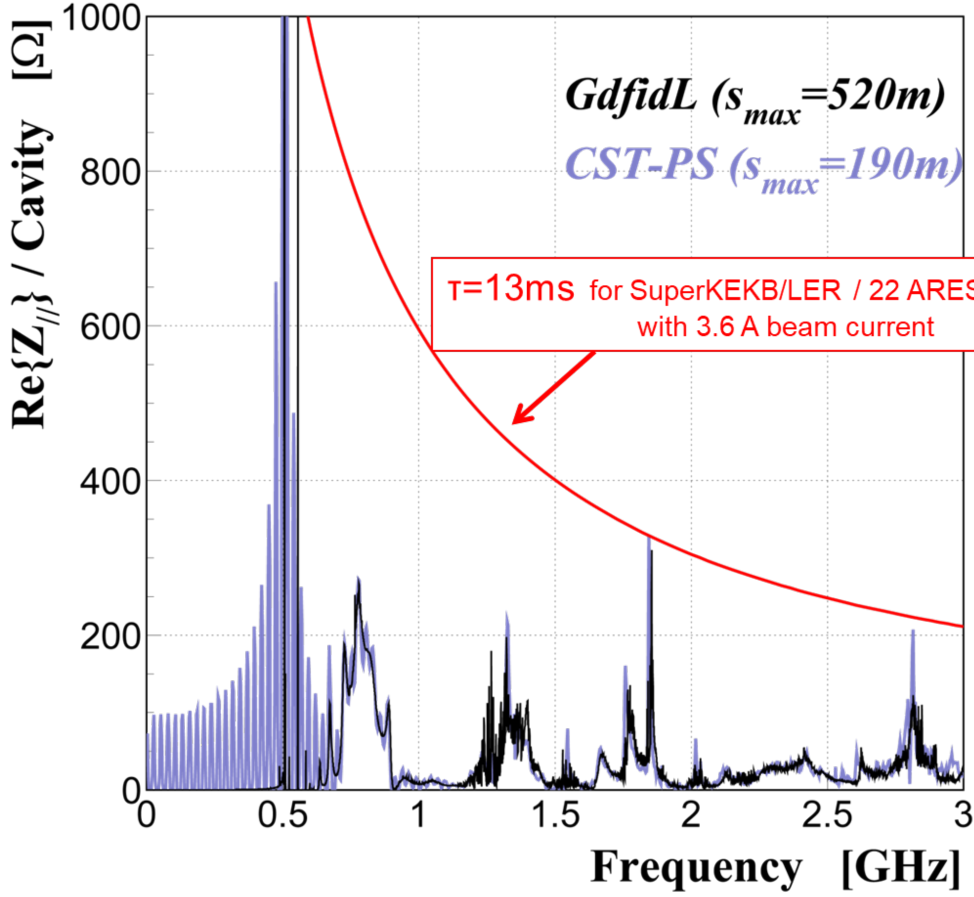
Appendix A (4/5)

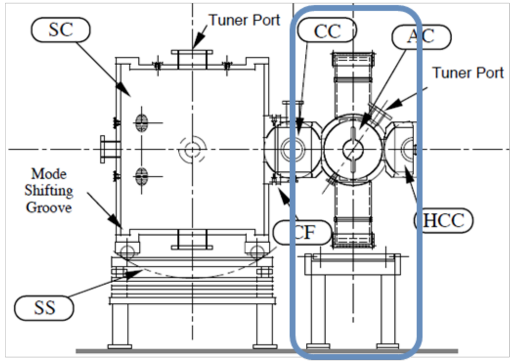
Longitudinal HOM Impedance *(Simulation Results)* and CBI Threshold at SuperKEKB/LER

Both impedances from wakepotentials in time-domain



← With the full structure (including SC)

← Only AC + half CC (without SC)



✓< 21.6 ms (Longitudinal rad. damping time of LER)
✓Fastest longitudinal CBI source
✓To be cured by the longitudinal bunch-by-bunch feedback system