RF system

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KEKB Accelerator Review Committee 2022

Dec. 13, 2022

Contents

- Overview of RF system
- Operation Status in 2022ab
- Maximum Beam Current Limited by Present RF system
  - RF Power delivered to Beam
  - Large HOM Power absorbed by HOM Dampers in SCC modules
  - Stability analysis of RF accelerating mode
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Overview of RF system

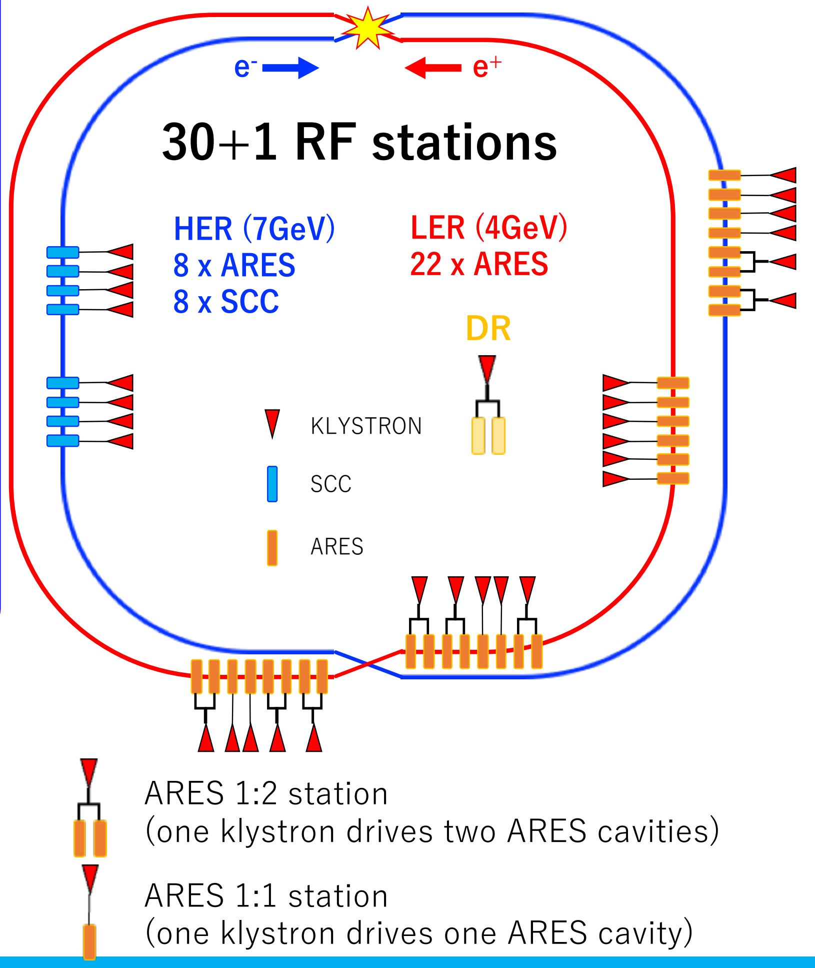
Re-use with reinforcements to handle twice high beam current and large beam power

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**

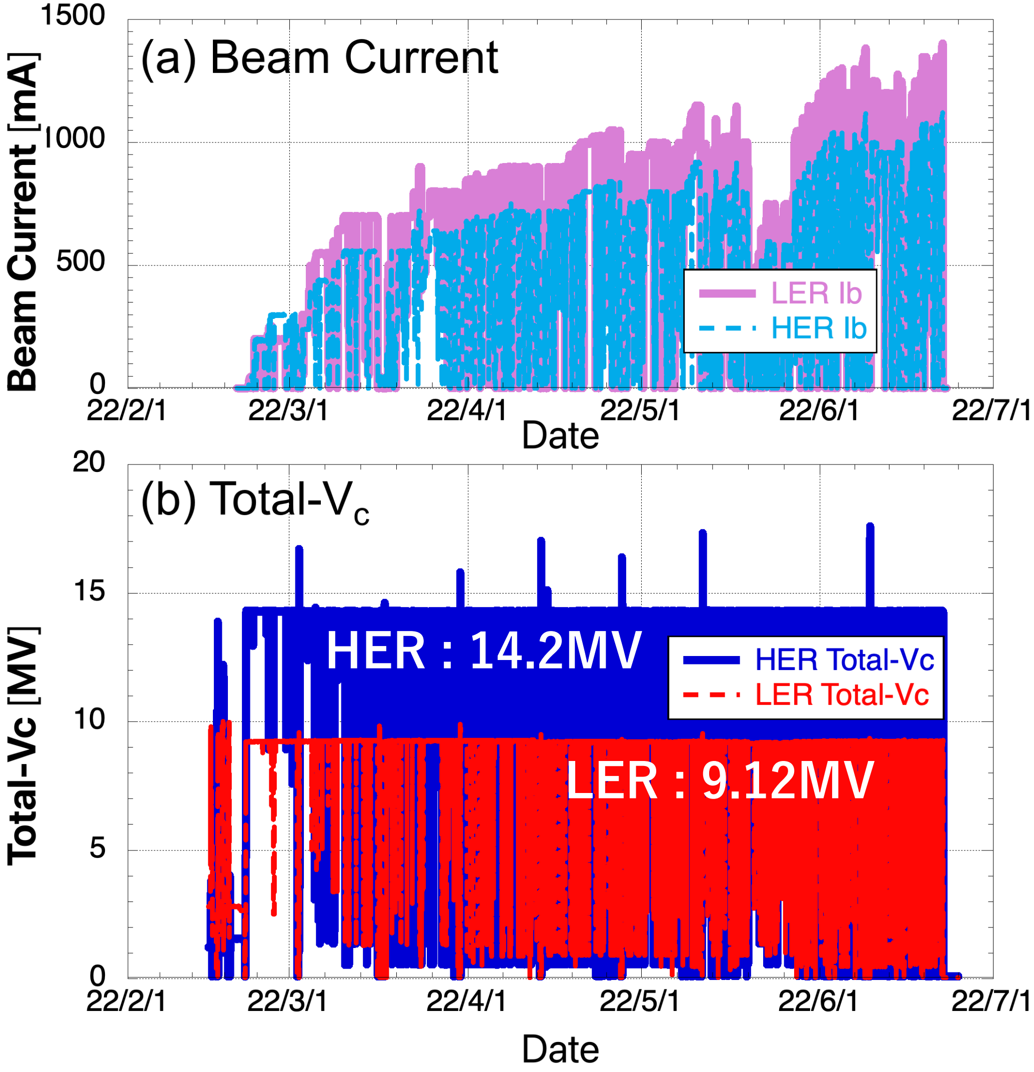
Parameter	Present (achieved) SuperKEKB				
Ring	HER			LER	
Energy [GeV]	7.0			4.0	
Beam Current [A]	**1.14**			**1.46**	
Number of Bunches	2346			2346	
Bunch Length [mm]	~6			~6	
Total Beam Power [MW]	~3.1			~3.2	
Total RF Voltage [MV]	14.2			9.12	
	ARES		SCC	ARES	
Number of Cavities	4	4	8	12	10
Klystron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

Present RF Layout



In the upgrade from KEKB to SuperKEKB, increasing the number of RF stations of ARES 1:1 configuration is essential to provide the large beam power.
At present, **the upgrade has been completed partially.**

Operation Status in 2022ab

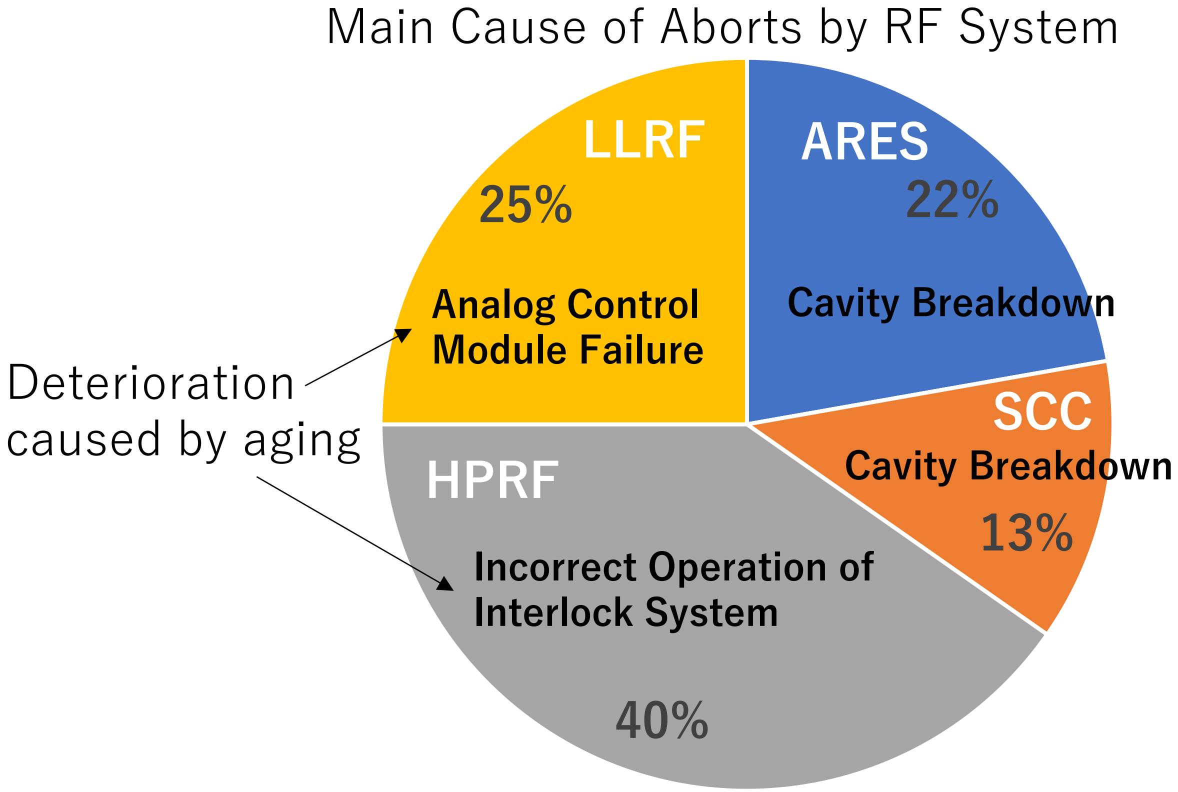


- The RF system of MR and DR are operating stably without critical troubles requiring long shutdown.
- The total-Vc for both rings of MR were kept as 9.12 MV for LER and 14.2 MV for HER through the run.
  - ARES : 0.40~0.45 MV/cavity, DR : 0.5 MV/cavity
  - SCC : 1.35 MV/cavity
- Longitudinal coupled bunch instability (CBI) due to RF accelerating mode is not a problem by CBI dampers.
- Major troubles (took > 1 hour to recover)
  - Failure of interlock system in Klystron power supply (ARES 1:1 station, D07C, LER)
    - Due to deterioration by aging
    - The corresponding ARES cavity had to be detuned.
    - Total-Vc was able to be maintained by increasing Vc of other cavities.
  - Failures of analog control modules
    - Due to deterioration by aging
  - Failure of frequency tuner system of SCC
    - Due to mistakes during assembling
    - Replaced the tuner

Beam Abort due to RF system

The number of Beam Aborts in 2022ab Operation
(excluding Manual aborts)

Cause of Abort		Count	
Total		725 (I_b>50mA)	
RF system		72 (0.6 /day)	
	ARES	16	30 cavities
	SCC	9	8 cavities
	HPRF	29	31 klystrons
	LLRF	18	31 systems



RF system is operating stable.
Main cause of beam aborts by RF system is the deterioration caused by aging.
For more stable and long-term operation, we will continue to conduct regular inspections and update equipment of RF system.

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High Beam Current-related issues in RF system

- Limitations of beam current due to the present hardware of RF system
  - **RF Power delivered to Beam**
    - Evaluate the maximum beam current that can be stored with the present RF system
  - **Large HOM Power absorbed by HOM Dampers**
    - Large cooling capacity of water will be also required.
    - Evaluate the allowable beam current with the present hardware setup
- Beam instabilities and issues
  - Some systems to cope with instabilities due to high 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 has been established and is working well. (K.Hirosawa et al., NIM A 953(2020)163007)
    - **Zero-mode related to Robinson stability**
      - Direct RF feedback (DRFB)
      - Zero-mode damper (ZMD)
      - The stability analysis in SuperKEKB operation conditions (K. Akai, PRAB 25, 102002 (2022))
  - Bunch Gap Transient
    - Propose the measures to mitigate the phase difference (T.Kobayashi and K.Akai, PRAB 19, 062001 (2016))

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RF Power delivered to Beam

based on Akai-san's Report in Aug. 2021

- Addition of RF stations has been completed **partially**.
- **In the design RF stations configuration (ex. report by K. Akai, at the 21th ARC (Jun. 13, 2016)), it was set as a prerequisite that the design current should be supported even with idling one or two RF stations due to malfunction.**
- **But considering the stable operation of RF system so far, as well as difficult budget situation we are confronted, we evaluated maximum stored current that can be stored with the present RF configuration without adding klystron stations, by focusing RF power delivered to beam.**

		LER		HER		
		ARES (1:1)	ARES (1:2)	ARES (1:1)	ARES (1:2)	SCC
KEKB	# Cavities	0	20	2	10	8
	# Klystrons	0	10	2	5	8
SuperKEKB/Present	**# Cavities**	**10**	**12**	**4**	**4**	**8**
	# Klystrons	**10**	**6**	**4**	**2**	**8**
SuperKEKB/ultimate	# Cavities	14	8	8	0	8
(design)	# Klystrons	14	4	8	0	8

Parameters for evaluation

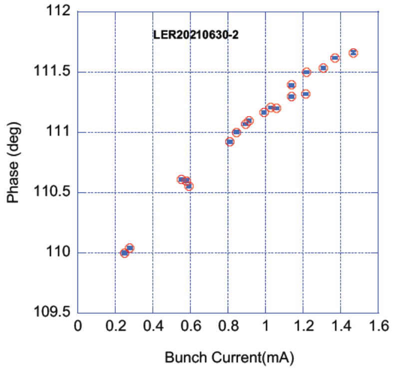
	ARES	SCC
R/Q	15Ω	93Ω
Q_0 or Q_L	$Q_0 = 1.1 \times 10^5$	$Q_L = 5 \times 10^4$
Input coupling β	5.0 (1:1), 2.7 (1:2)	--
RF voltage /cav.	0.5 MV	1.35 MV
Tuning offset	-5°	-8°

	LER	HER
Radiation loss	1.76 MV	2.43 MV
Parasitic loss	0.5 MV	0.5 MV
High power efficiency	0.93	0.93

parasitic loss： $V_{para} = k_{loss} \times (I_{beam}/N_b/f_{rev})$

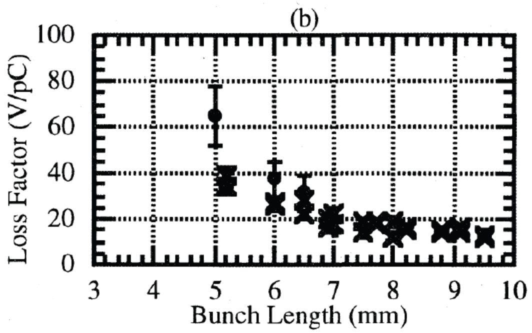
LER

飛山氏のsynchronous phase測定（2021年6月）結果から、$\Delta\phi_s/\Delta I_b$ = 1.5 deg/mAとして、k_{loss} = 24 V/pCと見積もる。設計ビーム電流値（I_{beam} = 3.6A, N_b = 2500）で V_{para} = 0.35 MV。



HER

家入氏のKEKBでの測定結果（下図のcrosses: 1999年、dots: 2003年）から、σz = 6～7mmで k_{loss} = 20～40 V/pC。設計ビーム電流値（I_{beam} = 2.6A, N_b = 2500）で V_{para} =0.21～0.42 MV。

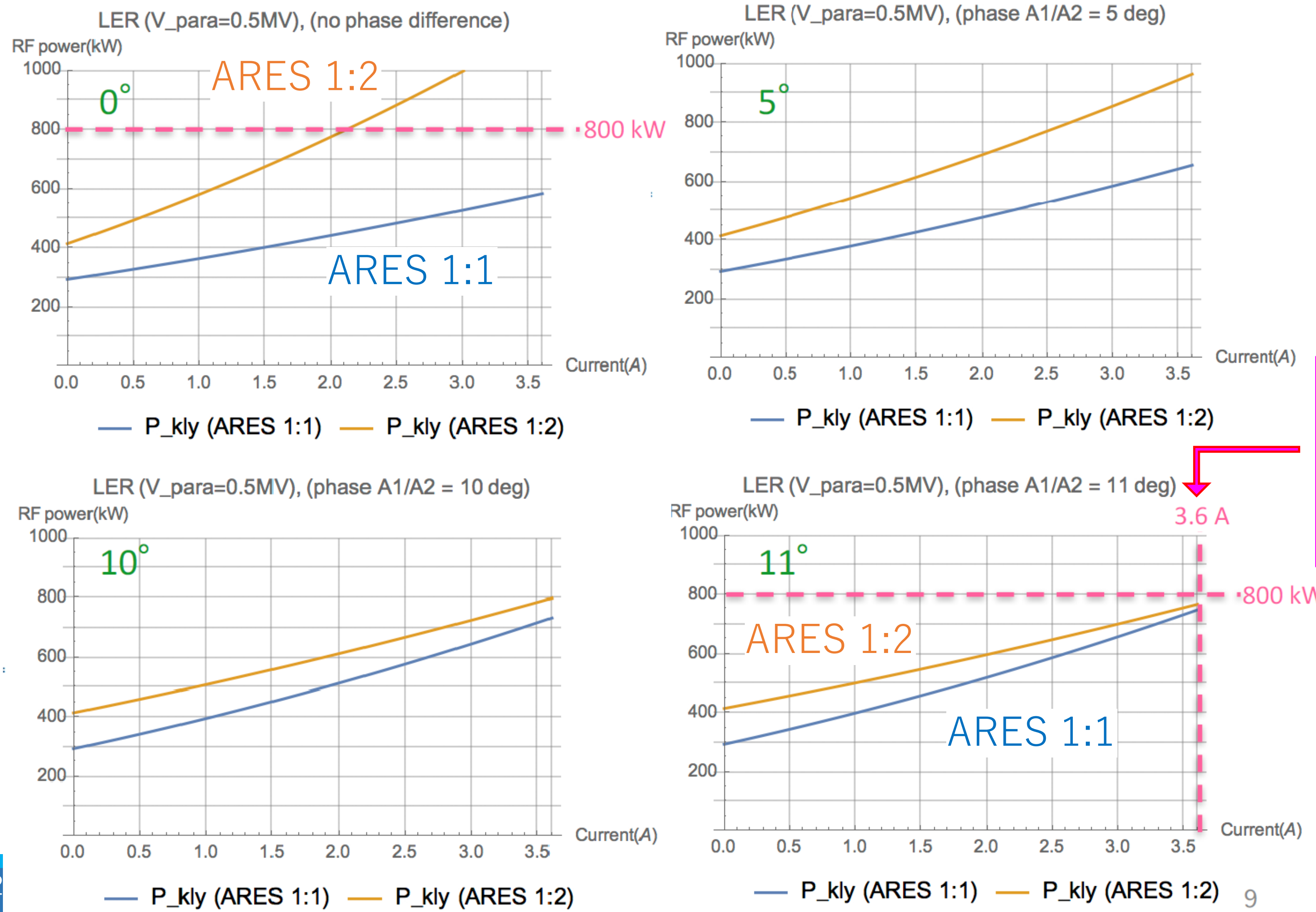


Evaluation method

- Calculate the Cavity input power (P_{in}) and the Klystron output power (P_{kly}) as a function of Beam current
- Set the maximum power to operate stable the RF system as
  - Klystron output power (P_{kly}) < 800 kW
  - Input power for ARES (P_{in}) < 750 kW
  - Input power for SCC (P_{in}) < 400 kW
- Scan the cavity phase to optimize the beam loading
  - Phase difference between ARES 1:1 and 1:2 stations
  - Phase difference between ARES and SCC stations
- Get the maximum beam current in the present RF system

LER (ARES 1:1 and 1:2 stations)

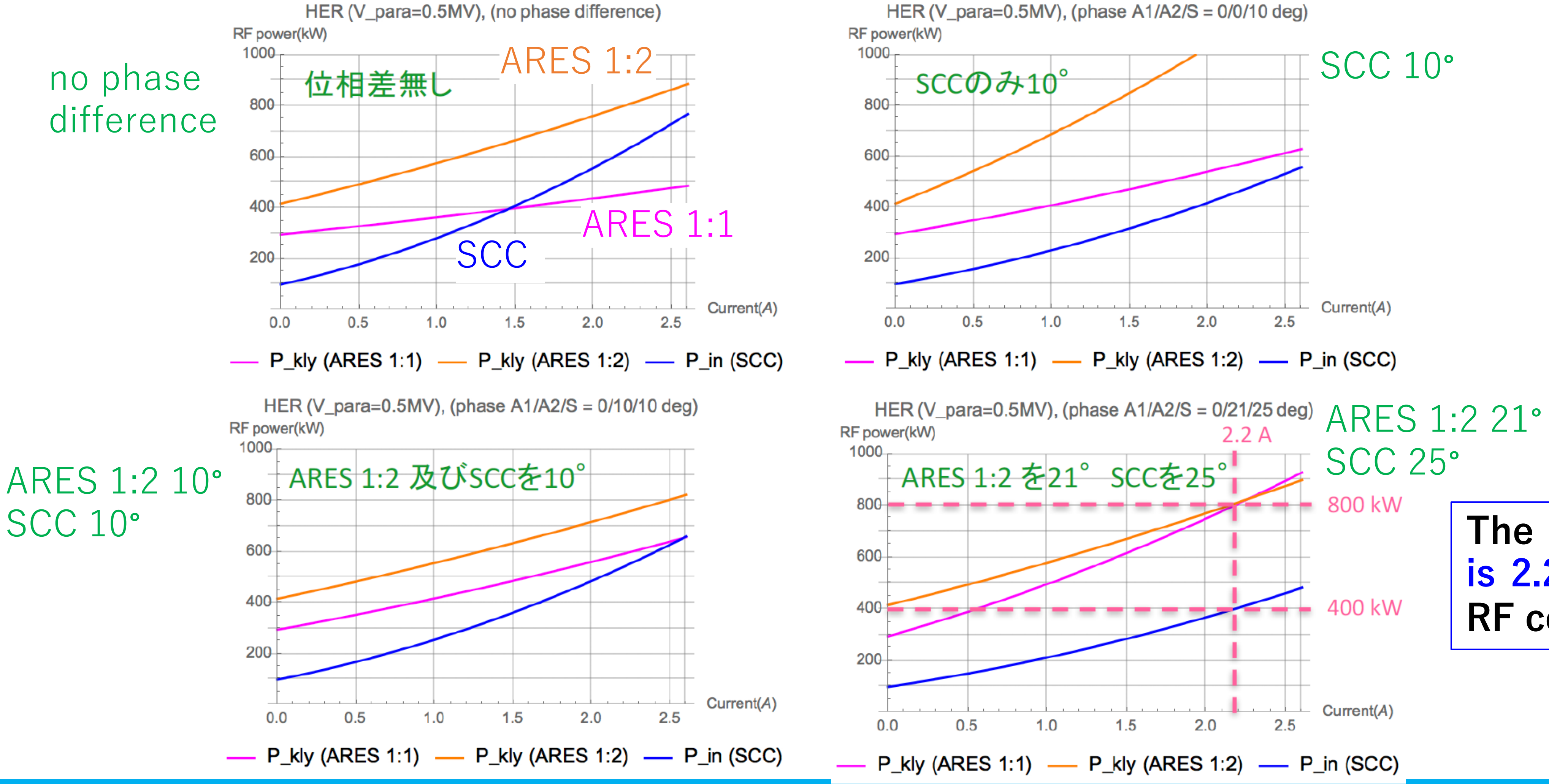
Relative Phase of ARES 1:2 station to ARES 1:1 station



Design current can be stored by optimizing the phase difference between ARES 1:1 and 1:2 stations.

HER (ARES 1:1, 1:2 and SCC)

Relative Phase of ARES 1:2 station and SCC station to ARES 1:1 station

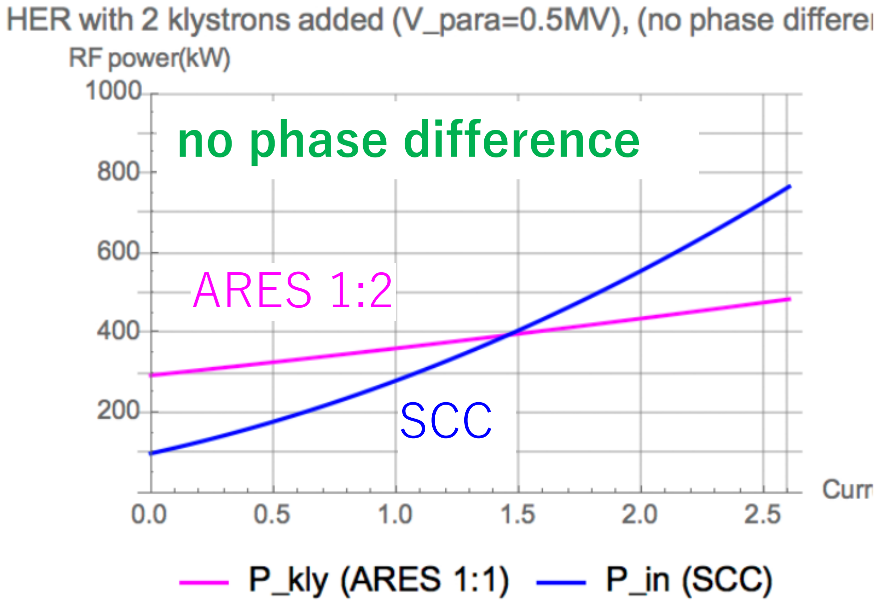


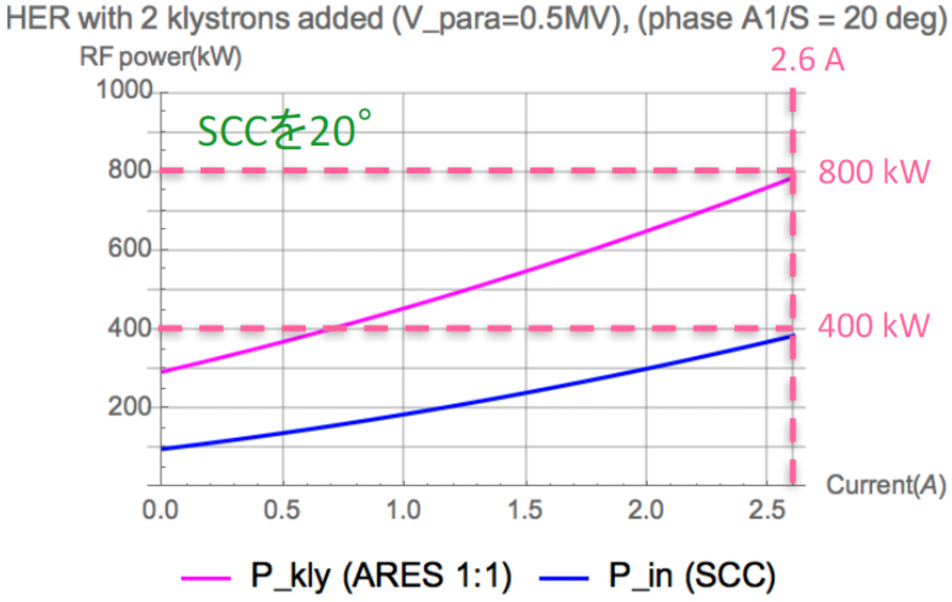
The maximum current is 2.2A by the present RF configuration.

HER with additional 2 RF stations

All ARES stations are 1:1 configuration.

Relative Phase of SCC station to ARES 1:1 station





In order to store the design current (2.6 A), adding two klystrons is necessary to convert four ARES cavities in the 1:2 configuration into 1:1.

Summary of Evaluation of RF Power delivered to Beam

- LER
  - **The RF power required to store the design current (3.6A) can be supplied by the present RF configuration.**
  - Because the number of wiggler magnets will decrease with the installation of NLC, the one-turn loss will decrease, which will further increase the margin of power.
- HER
  - **The RF power required to store the beam current of 2.2 A can be supplied by the present RF configuration.**
  - If a higher current is aimed in future, it is necessary to add RF stations in HER (2 klystrons for D04 section).

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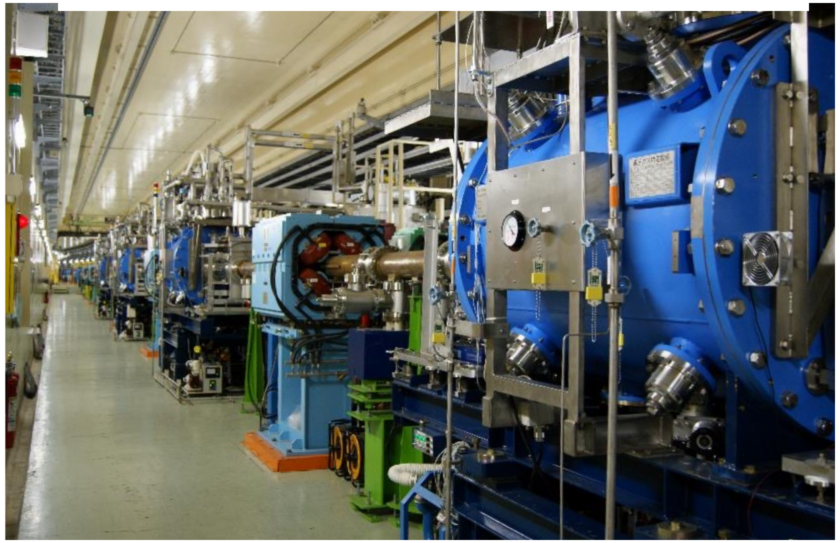
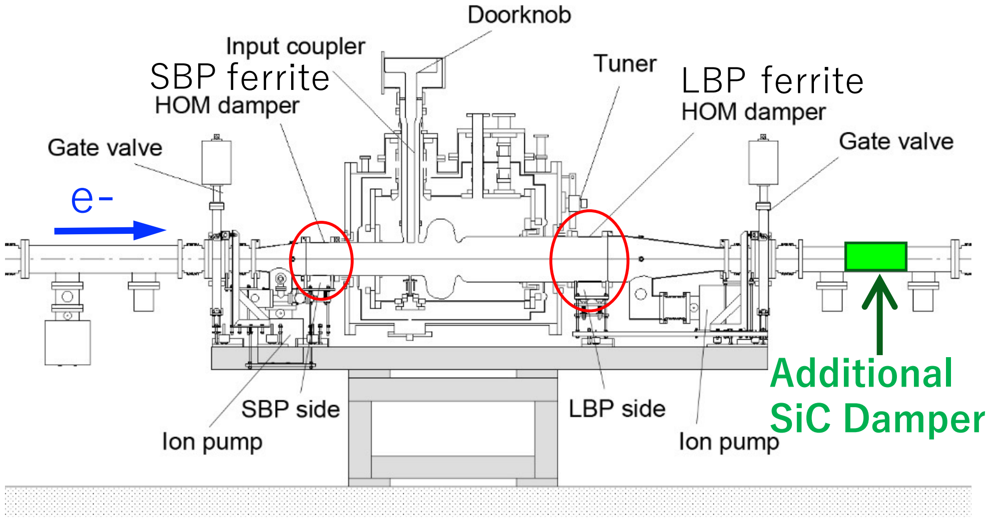
Large HOM Power absorbed by HOM Dampers in SCC modules

- The HOM power excited in one SCC is estimated as twice large as the maximum absorbed power by ferrite dampers in KEKB operation, 40% of which is emitted through the beam pipe to the downstream SCC module.
- To reduce the load of ferrite dampers of downstream SCC module, installing **additional SiC dampers** are needed to the downstream of SCC modules.
- Two SiC dampers have been installed to two SCC modules. It was confirmed that the additional SiC damper is effective to reduce the load of downstream cavities in beam operation. For the future high current operation, SiC dampers will be installed to all SCC modules.
- **The allowable beam current in the present hardware setup** (including update planed in LS1) is evaluated from the HOM power absorbed by ferrite dampers in the recent operation.

SCC Modules in SuperKEKB Tunnel





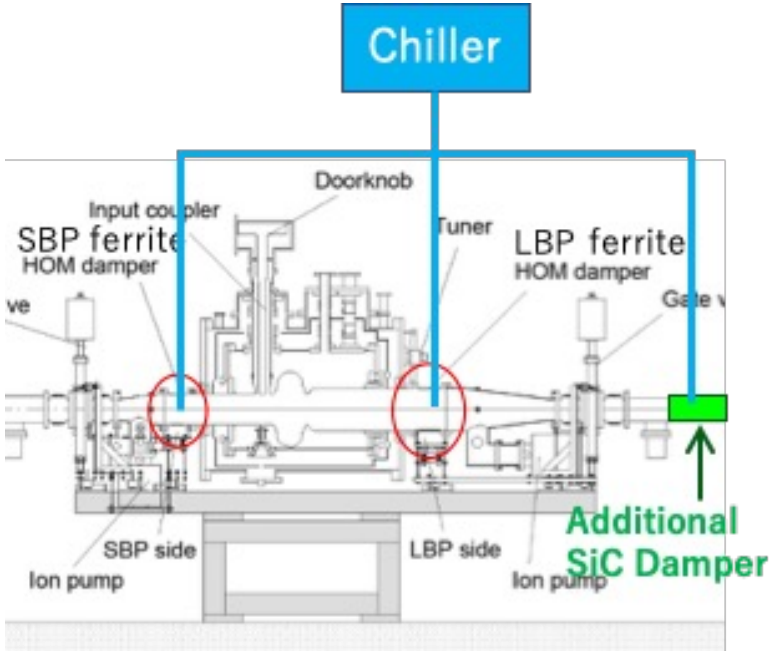
HOM Power Limit from the present hardware setup

- ●Cooling capacity of chiller

  ≦ **25 kW/module**

  ≦ **35 or 46kW/module with SiC damper**

  - Cooling water for HOM dampers belonging one SCC module are cooled by one chiller. Now, we have only 25 kW chillers. In LS1, we plan to update chillers of the modules with SiC damper to larger capacity one.
  - **Capacity of cooling water for chillers from infrastructure is also tight.**



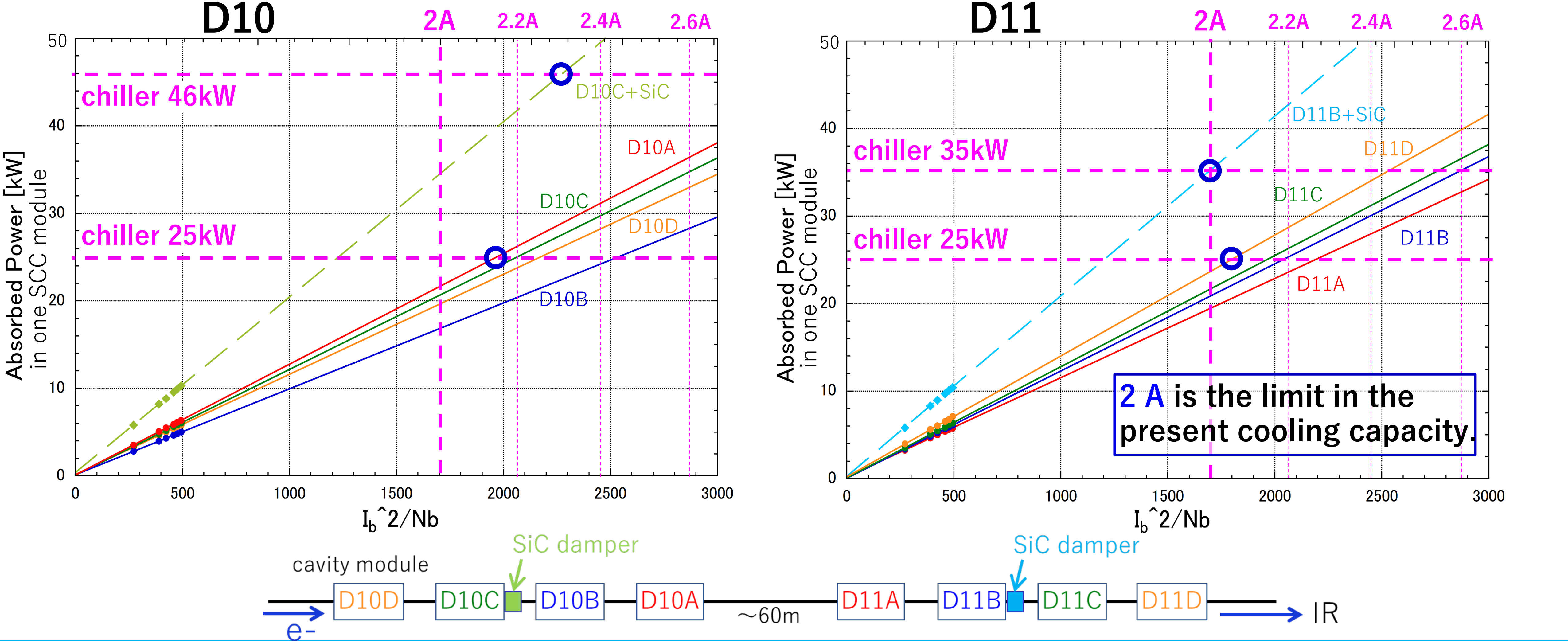
- ●Temperature of copper duct ≦ 60°C
  - The ferrite is HIPped on copper duct.
  - To prevent ferrite cracking
- ●Water flow speed (flow rate) ≦ 8 L/min
  - To avoid the erosion-corrosion of cooling pipe

} **12 kW for SBP**
18 kW for LBP

Evaluation of Allowable Beam Current

Limited by Cooling capacity of chiller for each module

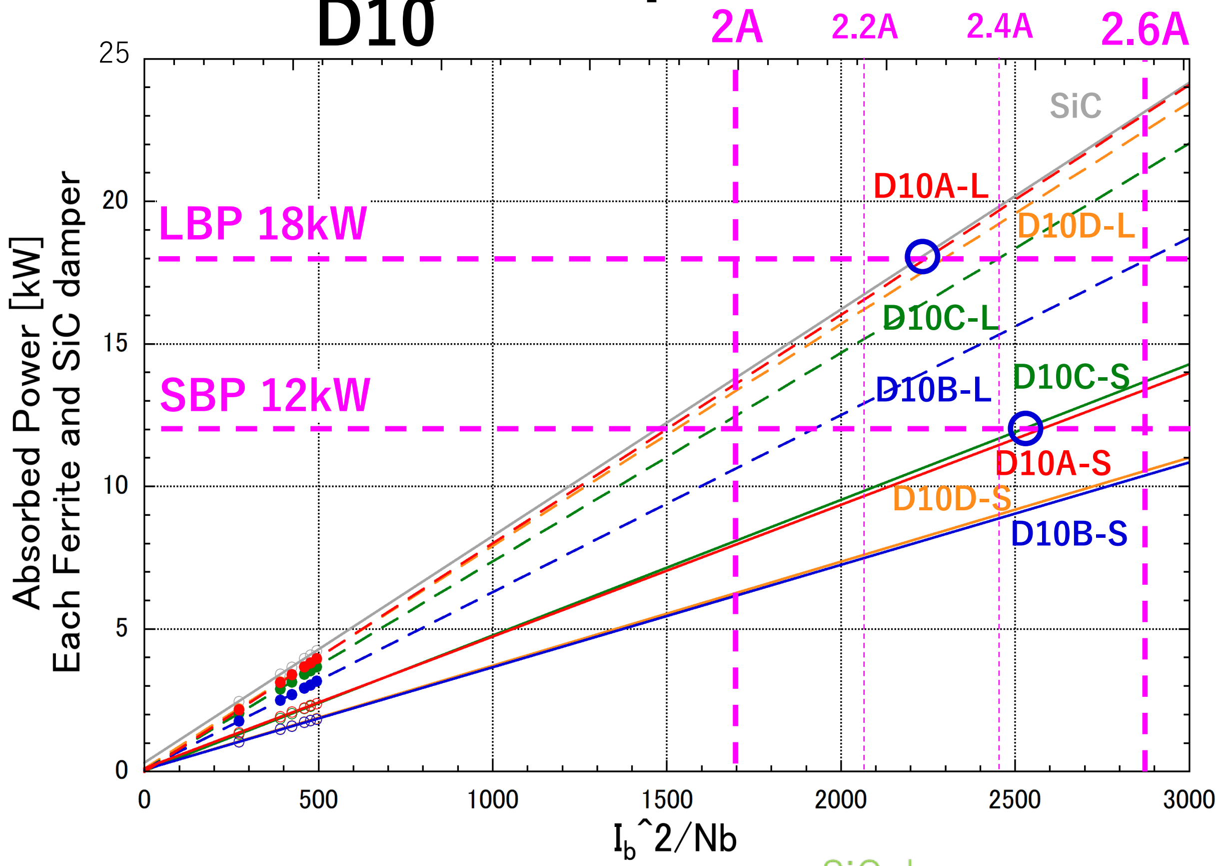
Nb= 2346 bunches

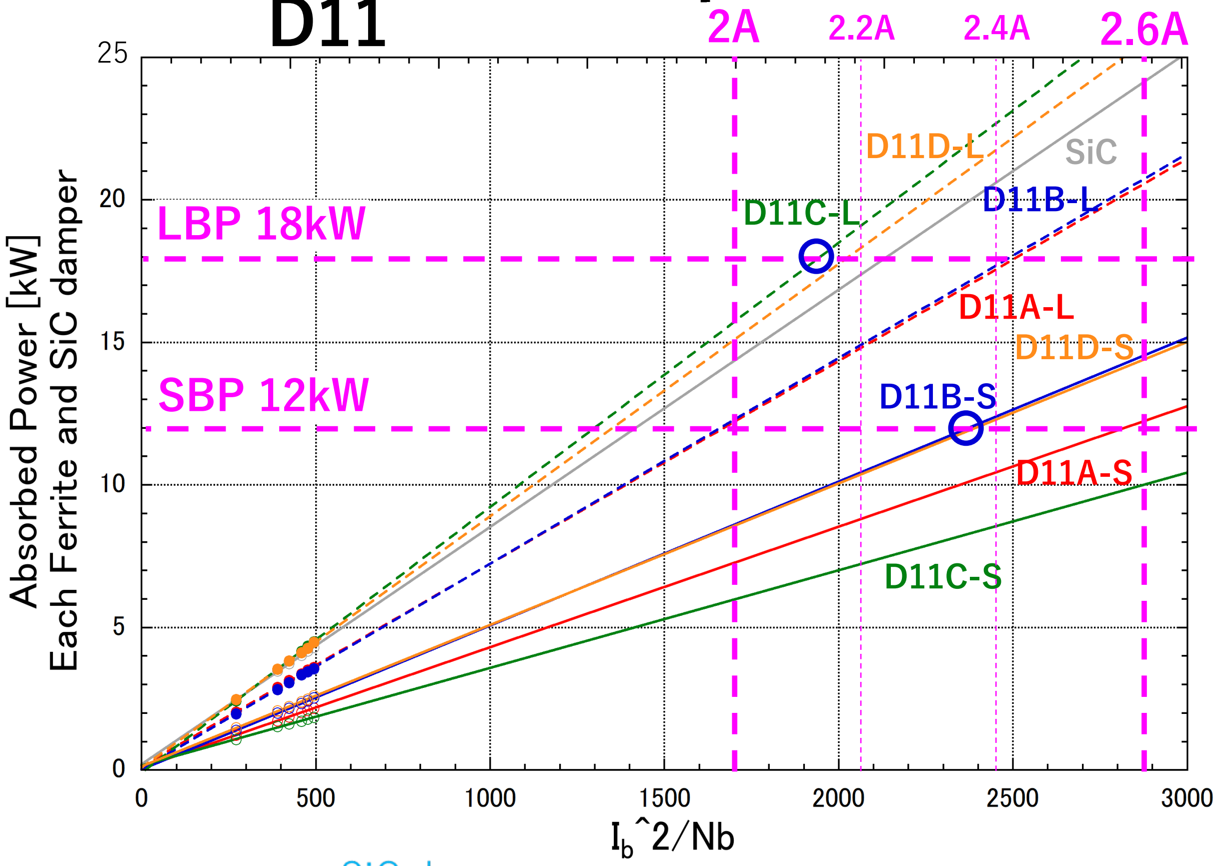


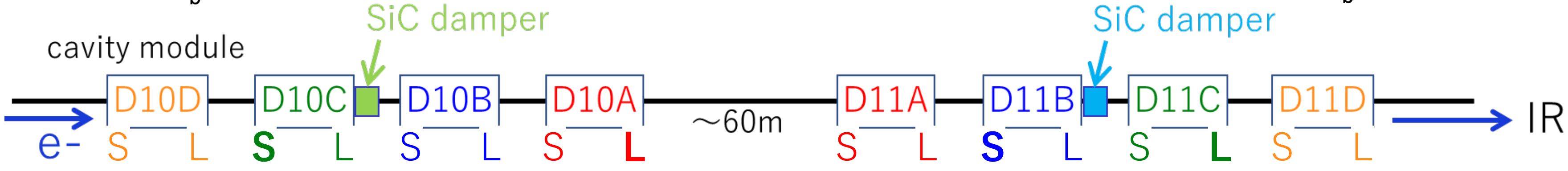
Evaluation of Allowable Beam Current

Limited by Temperature and Flow Rate for each damper

Nb= 2346 bunches







Summary of Evaluation of HOM power in SCC

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

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

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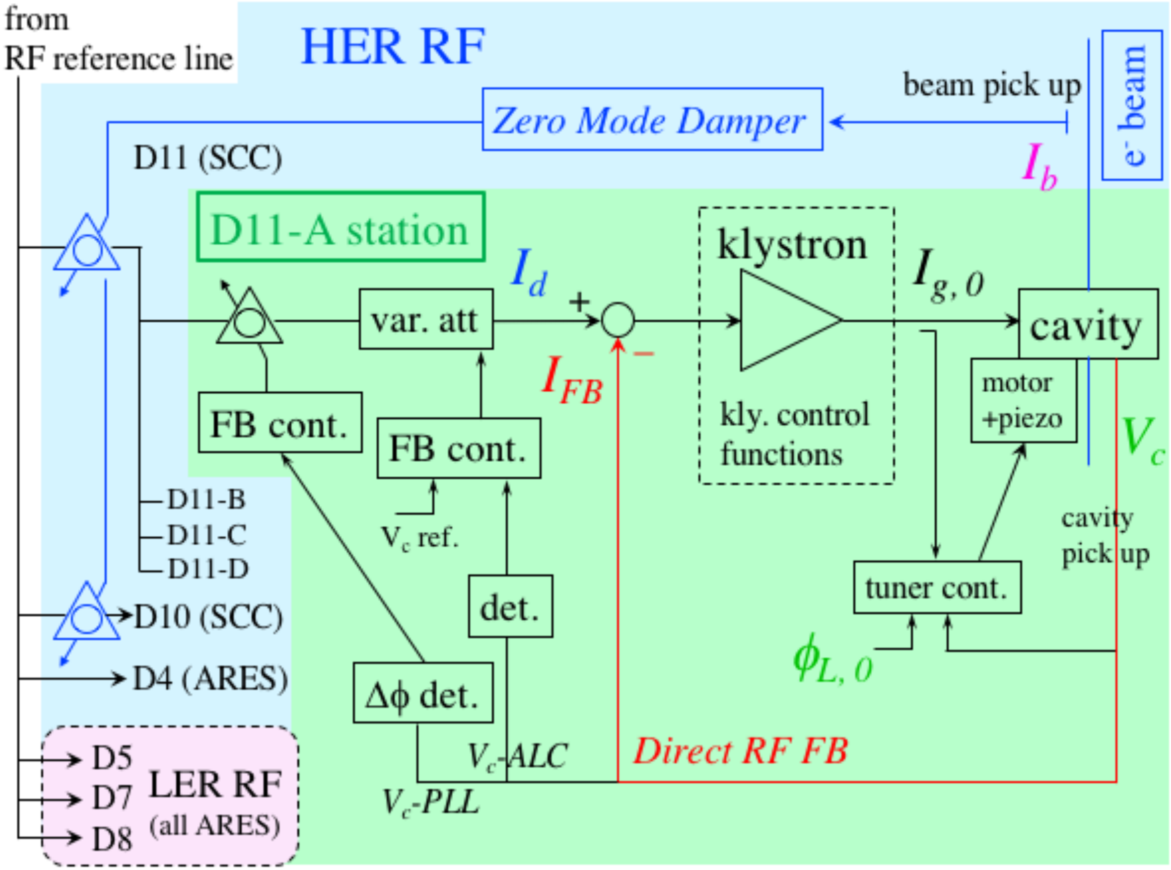
K. Akai, PRAB 25, 102002 (2022)

Stability analysis of RF accelerating mode

- Purpose of this study
  - Under the heavy beam loading, in addition to the Robinson limit, the stored current can be limited by the interaction between the cavity control loops and beam. The issue is a more serious problem in the HER because of high impedance of SCC.
    - The study revealed that this is also an issue in the LER, where only ARES cavities are used.
  - For further luminosity improvement of SuperKEKB in future, the stability of the accelerating mode (zero mode) is studied to check if it sufficiently secure increasing of the beam current aiming for the design values, as well as to identify necessary measures in the RF system.
  - (The modes such as -1, -2, -3, associated with the accelerating mode, has little coupling with the control loops. They are cured by the dampers for each mode independently.)

System description



Schematic view of the LLRF system for SuperKEKB, while highlighting one SCC station (D11-A) in the green colored part.

- The cavity voltage V_c is controlled by an auto-level control loop (ALC) and phase-lock loop (PLL). The bandwidth is 0.3 to 3 kHz.
- The direct RF feedback (DRFB) loop feeds pick up signal at the cavity back to the main RF line. The bandwidth of DRFB is determined mainly by the bandwidth of cavities (5~10 kHz).
- The zero-mode damper (ZMD) comprises a pickup monitor, down converter and BPF. The beam phase oscillation signal is fed to a phase shifter such that the driving RF is modulated to damp the oscillation.

- Cavity tuning is performed mechanically. The time constant is on the order of 1 Hz, much slower than that of ALC, PLL, and DRFB.
- The effects of the klystron control functions are localized around the klystron, with little interaction with beam dynamics.

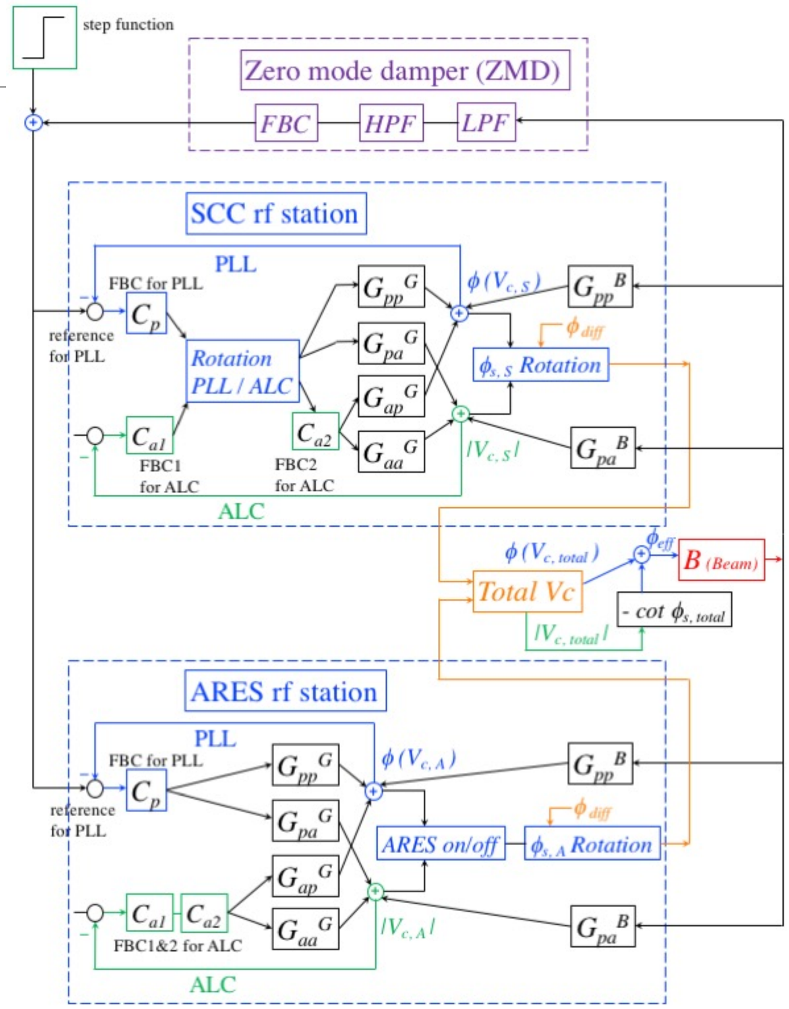
Analysis methods

Two independent methods are used for the analysis:

Method 1: The characteristic equation (CE) for the system is set up with the transfer functions (TF) for each component. The solutions for the CE provide the dynamical performance of the system.

Method 2: Using time domain simulation MATLAB/Simulink. The right figure shows a schematic view of the block diagram created as the input data for the simulation using MATLAB/Simulink. It comprises an SCC part, an ARES part, and the ZMD.

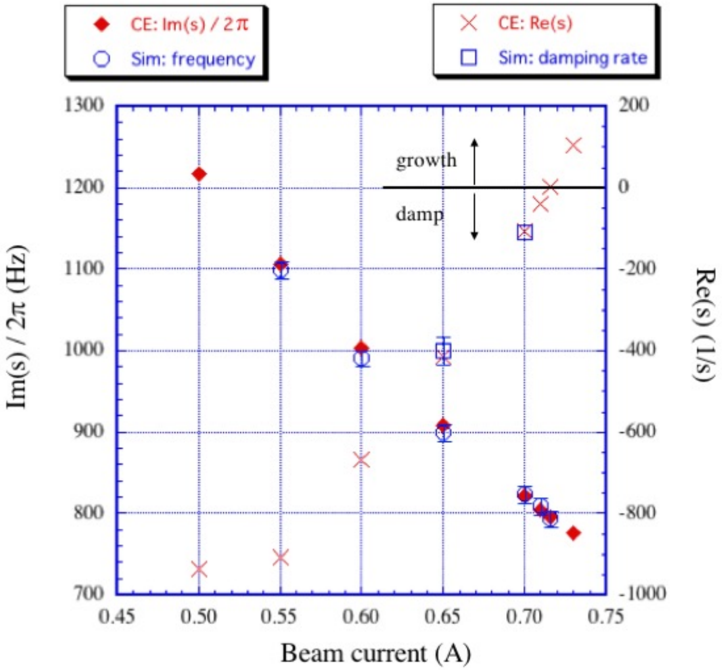
We extended the TF in the Pedersen model to include the DRFB loop, while coexisting with the other control loops such as the amplitude and phase controls.



Block diagram of the input data for the simulation using MATLAB/Simulink. It comprises an SCC part, an ARES part, and the ZMD.

Validation of the analysis

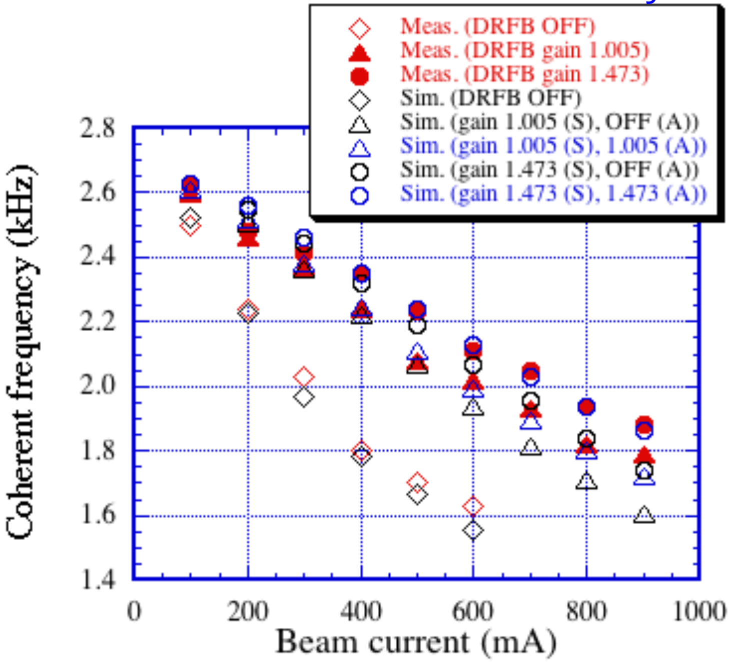
(A) Consistency between the two analysis methods



[**Red**]: Solutions of the CE corresponding to the zero-mode oscillation as a function of beam current.
[**Blue**]: The oscillation frequency and damping rate obtained from time-domain simulation.

Results of two analysis methods were consistent.

(B) Comparison of the simulation with measurement in a machine study



[**Blue** and **Black**]: Zero mode coherent frequency f_s obtained by simulation.
[**Red**]: The measured f_s in the machine study (Ref. (a)) are also plotted.

Ref (a): K. Akai et al., 17th Annual Meeting of Particle Accelerator Society of Japan, 2020.

The analysis and measurement results were in good agreement.

Application to SuperKEKB

- Having confirmed the validity of these methods, they were applied to extensively study the SuperKEKB RF system.
  - Firstly, the effectiveness of different control functions was examined for a simple system in the SCC case using CE and simulation.
  - Subsequently, the stability of the full RF system in the HER comprising the SCC and ARES with the ZMD was analyzed using simulations for various operation conditions.
  - The stability of LER RF system was also studied using simulations.
- Based on the results obtained above, possible operating conditions aimed at the design current were comprehensively investigated.
  - In beam operations, maximum achievable stored current may be considerably lower than the threshold current obtained from the analysis for different reasons such as non-linearities, fluctuations, and scattering of cavity performances.
  - Consequently, as reference guideline, a threshold current target value for the HER (LER) of 4 A (5 A) was set, which is expected to have a good margin (~1.5 times) for the design current of 2.6 A (3.6 A).
  - The results showed **effective measures to improve the stability** as follows:
    - ➢ **increasing the operating voltage of ARES** (with possibility after ample conditioning of the cavity)**,**
    - ➢ **the extension of ZMD to all RF stations,**
    - ➢ **reducing the gain or bandwidth of PLL and ALC within an acceptable range,**
    - ➢ **(option) implementation of the rotation function between PLL and ALC.**

    They can be implemented without requiring big budget. (Note that the necessity of adding two klystron stations comes from power requirement, which depends on the maximum stored current foreseen.)

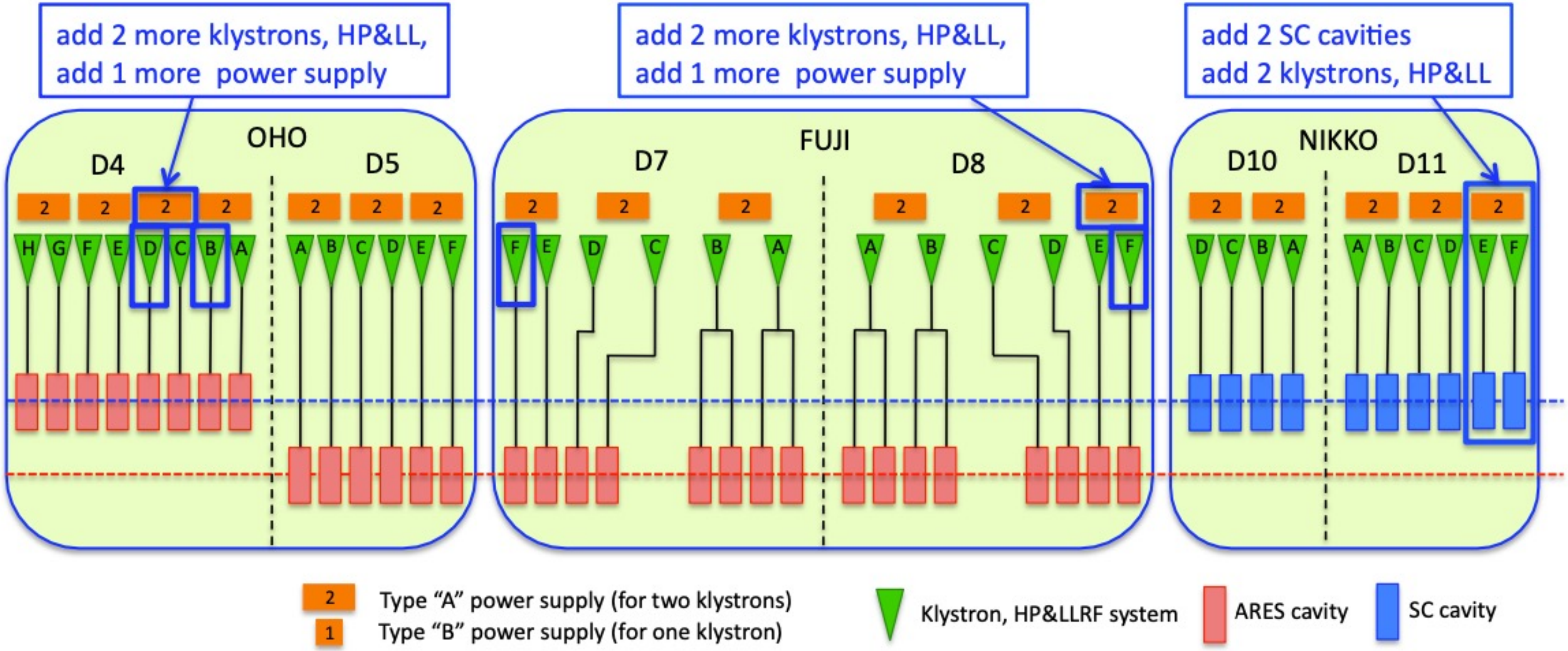
Summary

- RF system is operating stable.
- For more stable and long-term operation, we will continue to conduct regular inspections and update equipment of RF system.
- Beam current limit by the present RF system is evaluated.
  - RF power delivered to beam : LER 3.6 A (design), HER 2.2 A
  - HOM power absorbed by dampers : LER 2.6 A, HER 2.0 A
  - For HER, **the adding two RF stations** and **the reinforcement of the cooling capacity for HOM damper cooling** are necessary.
- Stability analysis of RF accelerating mode (zero mode) was performed in SuperKEKB operation conditions.
  - The results showed effective measures without requiring big budget to improve the stability. And the results could be used as guidelines for future beam operation by increasing the beam current step by step.

back up

More RF reinforcement plan to further increase beam current after Phase 2,

depending on budget, demand and machine performance.



Time required to add RF components

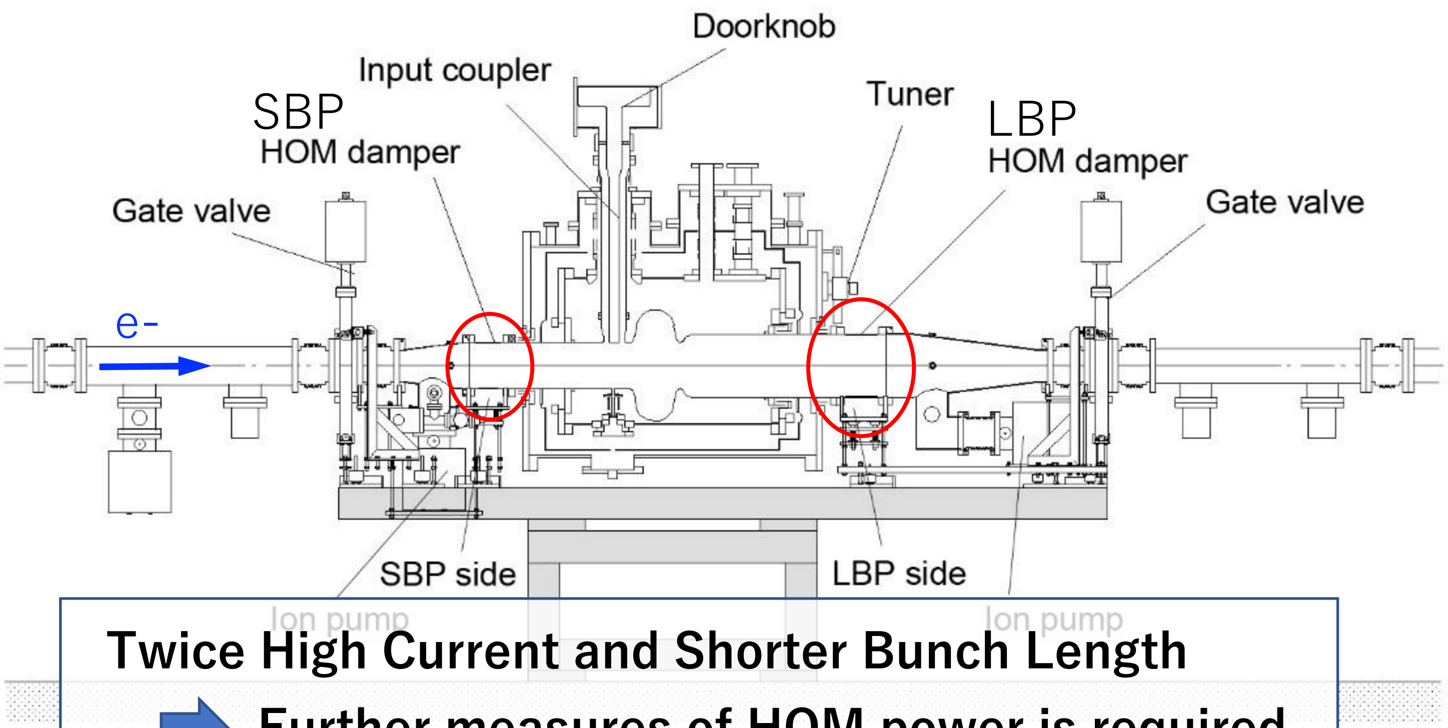
- To add two klystron stations
  - Two sets of klystrons, high-power systems and water-cooling systems, one set of klystron power supply and control system
  - Five sets of Digital LLRF systems

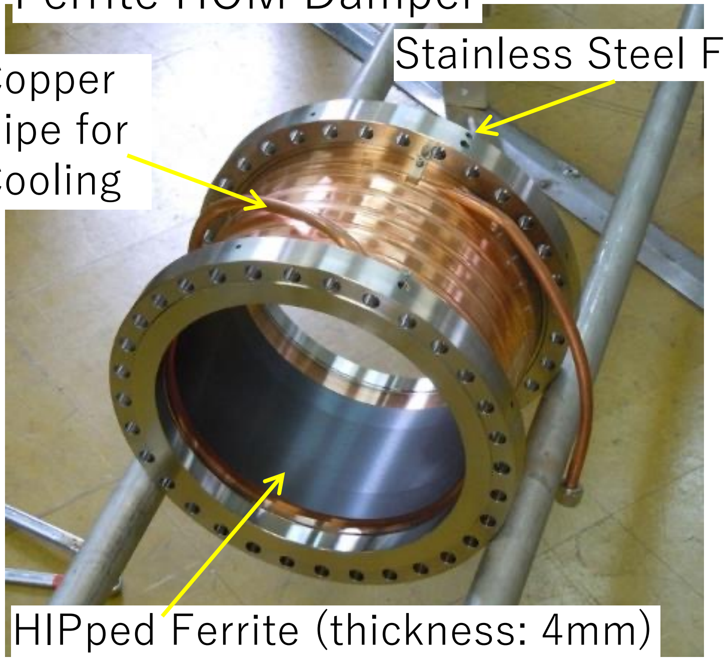
  → 3+ α years (including ~1 year for construction)
- To add SiC damper

  → 1 year for one set (possibility of shortening in mass production)

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)



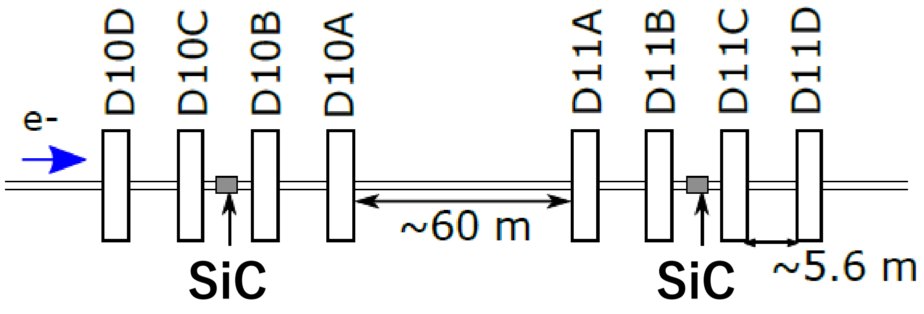


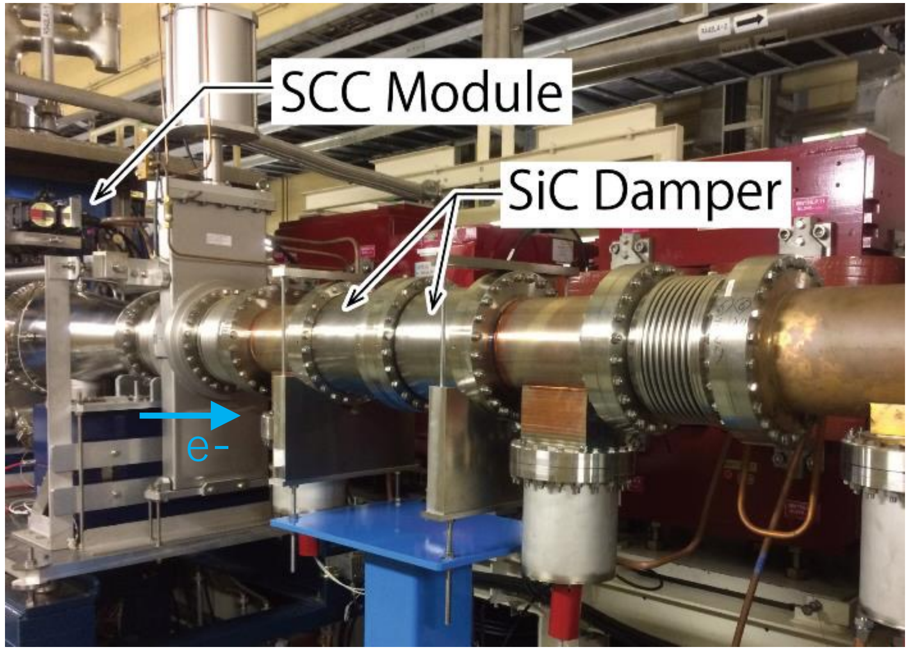
Twice High Current and Shorter Bunch Length

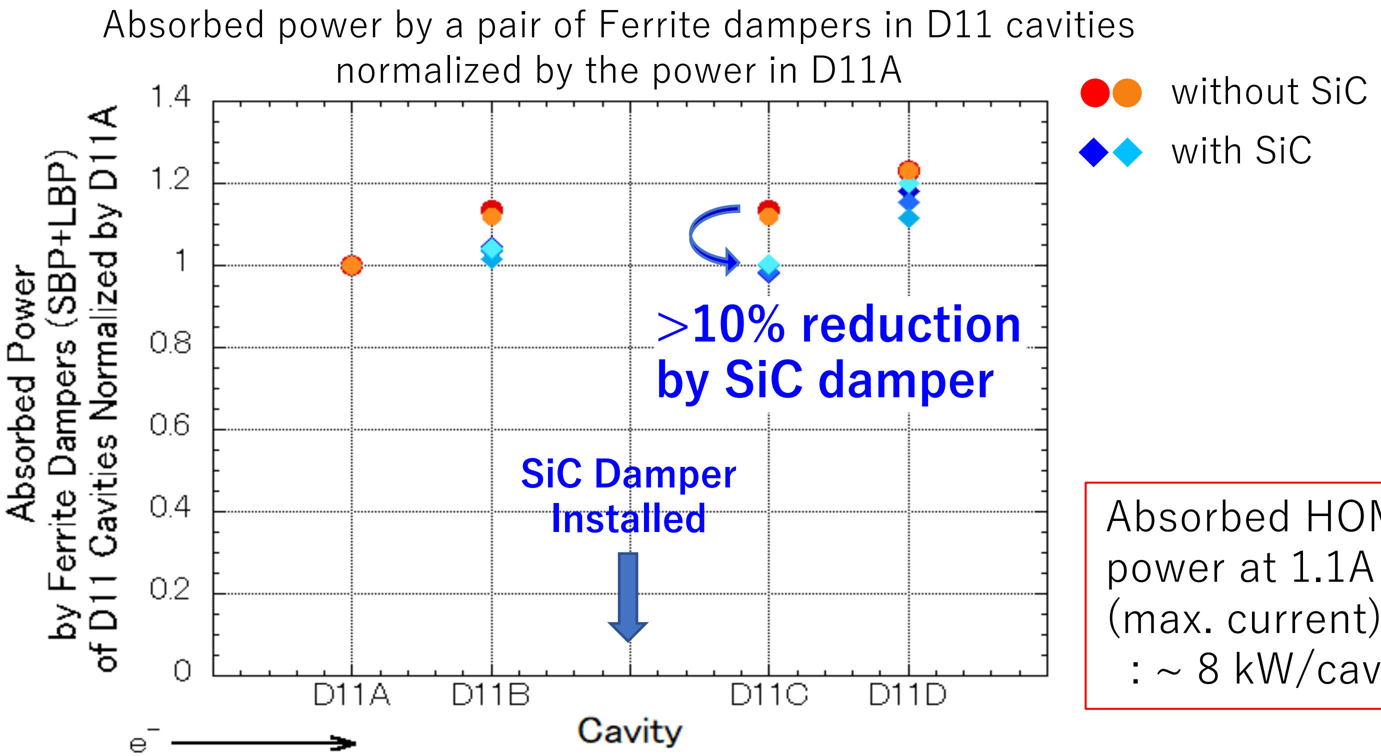
➡ **Further measures of HOM power is required.**

Results of Beam Test with SiC Damper

Layout of 8 SCCs and SiC dampers





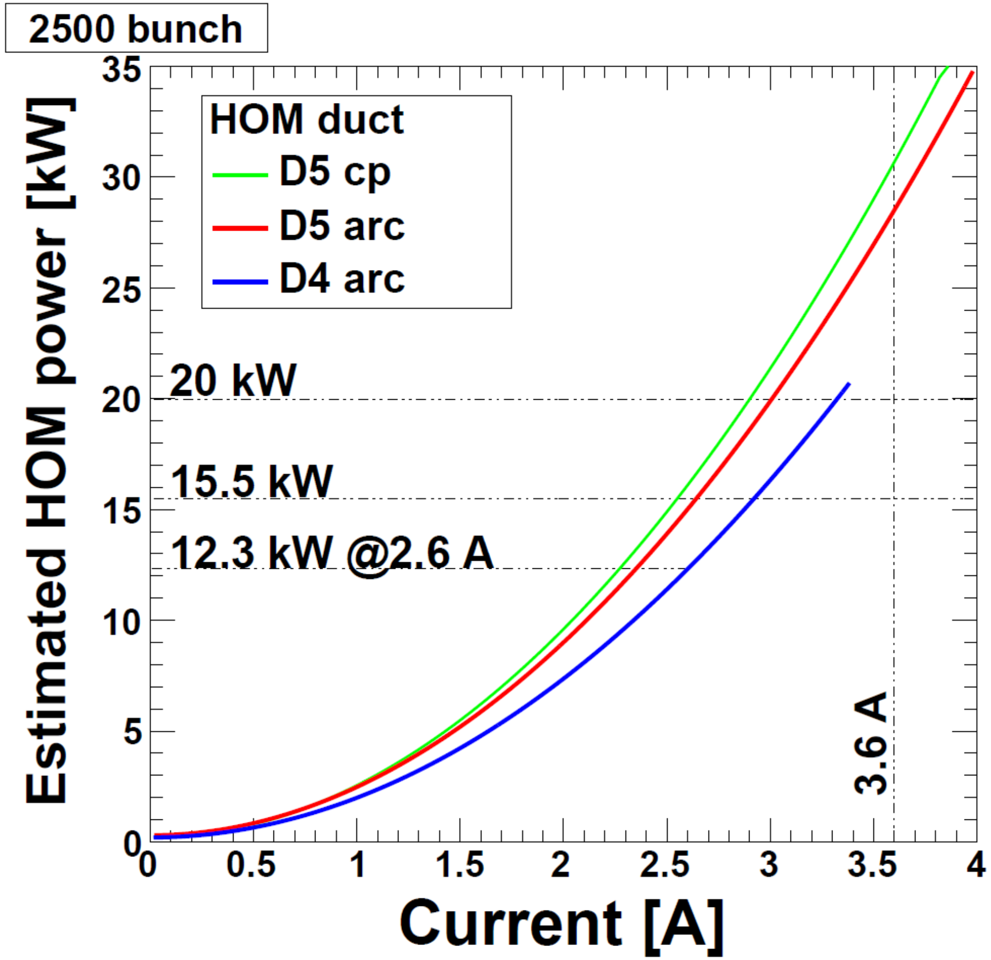


Absorbed HOM power at 1.1A (max. current) : ~ 8 kW/cavity

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.

Evaluation of HOM power absorbed by SiC damper in ARES section

S. Enomoto



Current tolerance [A]	D5 cp	D5arc	D4 arc
12.3kW(HER design)			2.6
15.5kW(achieved)	2.55	2.64	2.85
*20kW (cooling power upgrade)	3.0	2.9	