# Operational Experience of SRF Module in SuperKEKB with 1-A Beam Current

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WG3 on TTC2025 at IRIS/IBS, Daejeon, Korea

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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
- Upgraded from KEKB
- SuperKEKB accelerator complex consisting of;
  - Injector (Linac)
  - Positron Damping Ring (DR)
  - Beam Transport Lines (BT)
  - Main Ring (MR) with Belle II Detector

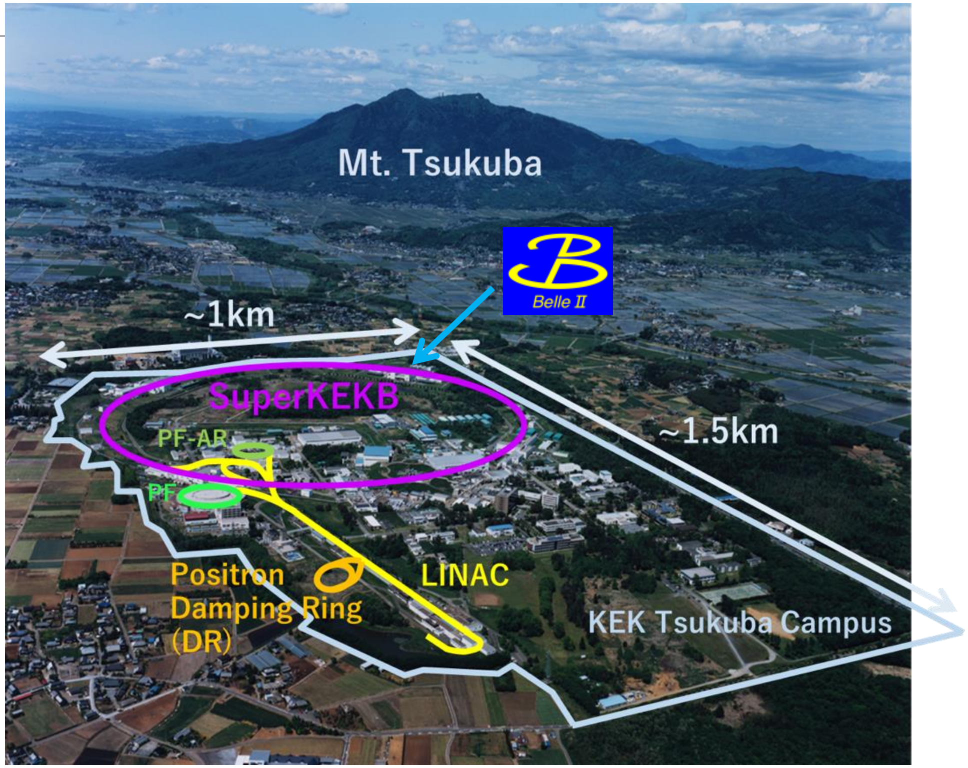
- Aiming **High Luminosity**

  on the order of $\mathbf{10^{35}\ /cm^2/s}$

  (several 10 times of KEKB achieved)

➢ **Nano-beam scheme (P. Raimondi)**
  - To counter Hourglass effect, collide the beams with very small beam size at large crossing angle
  - $\sigma_x = 10\ \mu\text{m}, \sigma_y < 100\ \text{nm}, 2\phi \sim 830\text{mrad}\ (\sim 5\text{deg.})$ at collision point

➢ **High Beam Current**
  - Twice higher than KEKB achieved beam current




| Design Parameters | LER (positron) | HER (electron) |
|---|---|---|
| Energy | 4 GeV | 7 GeV |
| Beam Current | 3.6 A | 2.6 A |
| Bunch Current | 1.44 mA | 1.04 mA |
| Circumference | 3016 m | |
| Number of Bunches | 2500 | |

# Operation History of SuperKEKB

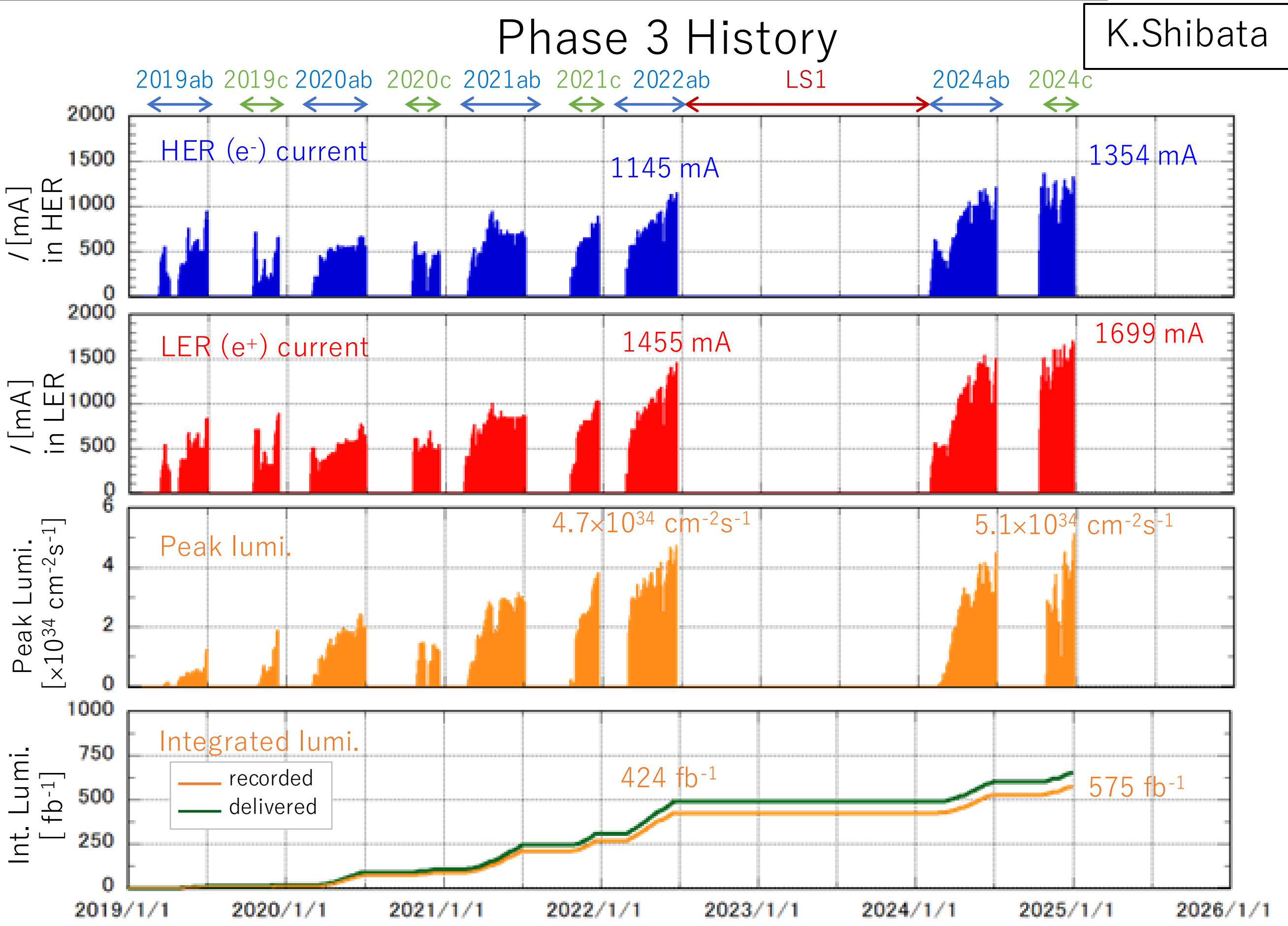
The commissioning operation was started in 2016.

- Phase1 (2016.Feb. - June);
  - Vacuum scrubbing, etc. w/o final focusing system (QCS) and Belle II detector
- Phase2 operation (2018.Mar. - July);
  - Pilot run of SuperKEKB and Belle II w/o pixel vertex detector (PXD)
- **Phase3 operation (2019.March-)**;
  - Physics run with fully instrumented Belle II detector.

**2024 autumn run (2024c)**

- Maximum Beam current
  **LER : 1.699 A, HER : 1.354 A**
- Peak Luminosity : **$5.11 \times 10^{34}$ /cm$^2$ /s**
- number of bunch : 2346
  2-RF bucket spacing (~4 ns spacing)

K.Shibata



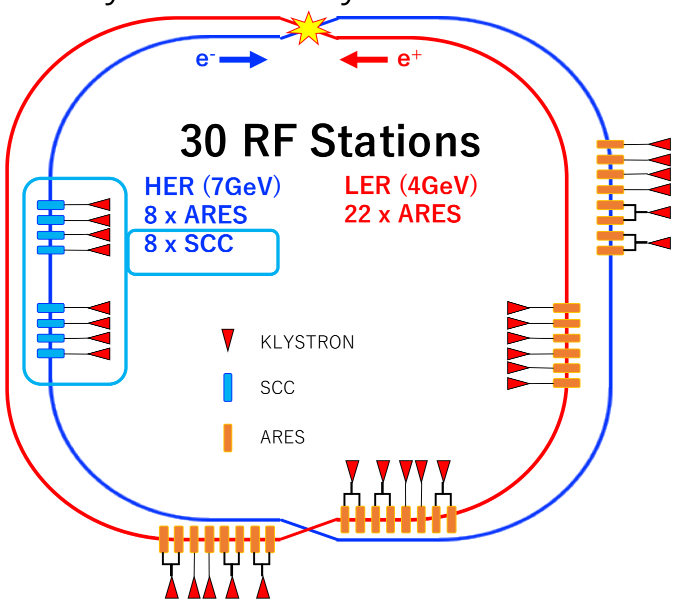

**Peak luminosity of $5.11 \times 10^{34}$ /cm$^2$/s was recorded in Dec. 2024.**

# Overview of RF System

The biggest challenges for RF system are high currents and large beam powers.

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

Layout of RF system in MR




RF-Related Parameters $f_{rf} \approx 509$ MHz

| Parameter | KEKB (achieved) | | | | SuperKEKB (design) | | | | SuperKEKB (2024c) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 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** | | **1.35** | | | **1.70** | |
| 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** | | ~3.7 | | | ~3.5 | |
| Total RF Voltage [MV] | 15.0 | | | 8.0 | 15.8 | | 9.4 | | 14.2 | | | 9.3 | |
| | 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 | | 0.40 | 0.45 | 1.35 | 0.40 | 0.45 |
| Beam Power [kW/Cav.] | 200 | 550 | 400 | 200 | 600 | **400** | 200 | 600 | ~100 | ~230 | **~300** | ~170 | ~230 |

### SC (superconducting) cavity

- Single-cell cavity, 1 cavity/module
- HOM damped structure
- 8 modules only in HER (e-)
- Max. Beam power : 400 kW/cavity (practical limit)
- RF Voltage : 1.5 MV/cavity

### Normal-conducting cavity (ARES)

- Unique three-cavity system specialized for KEKB
- HOM-damped structure
- HER (e-) : 8 cavities, LER (e+) : 22 cavities
- Max. Beam power : 600 kW/cavity (design)
- RF Voltage : 0.5 MV/cavities

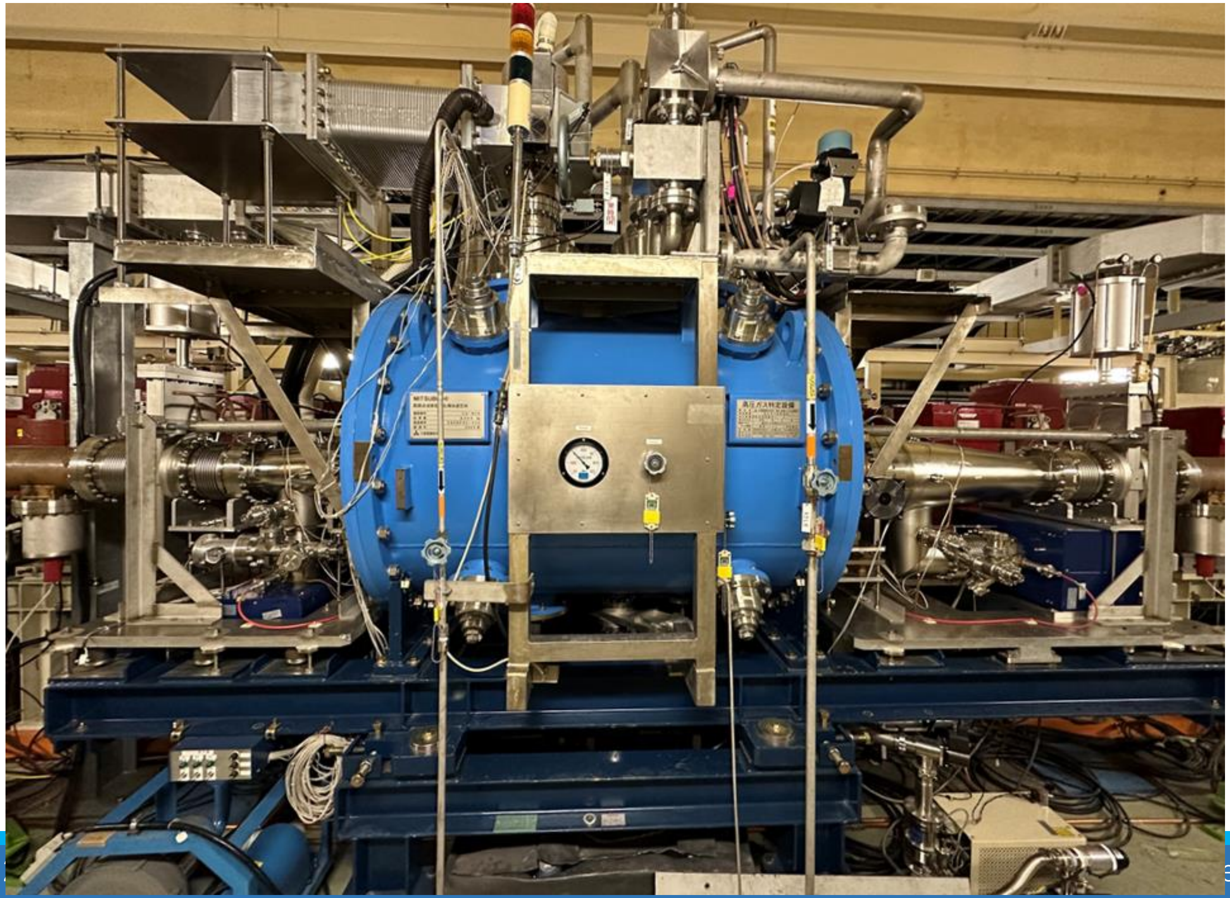
**The most unique feature of our RF system is the hybrid system of SCC and ARES.**

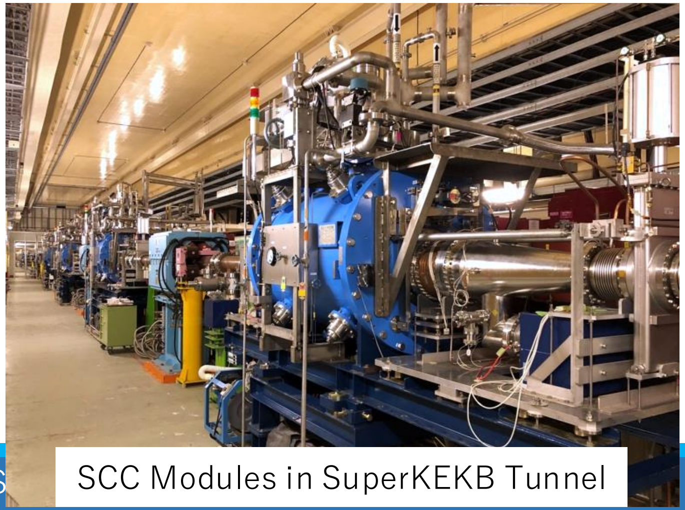
# SCC module in SuperKEKB

# SCC module in SuperKEKB

- 509 MHz niobium single-cell HOM-damped cavity, 4.4 K operation
- 8 SCC modules in HER (electron ring) & one spare module
- SRF system is reused from KEKB including cryogenic system.
- **Beam power of SRF will be kept the same as at KEKB by applying phase-difference and sharing with ARES cavities.**

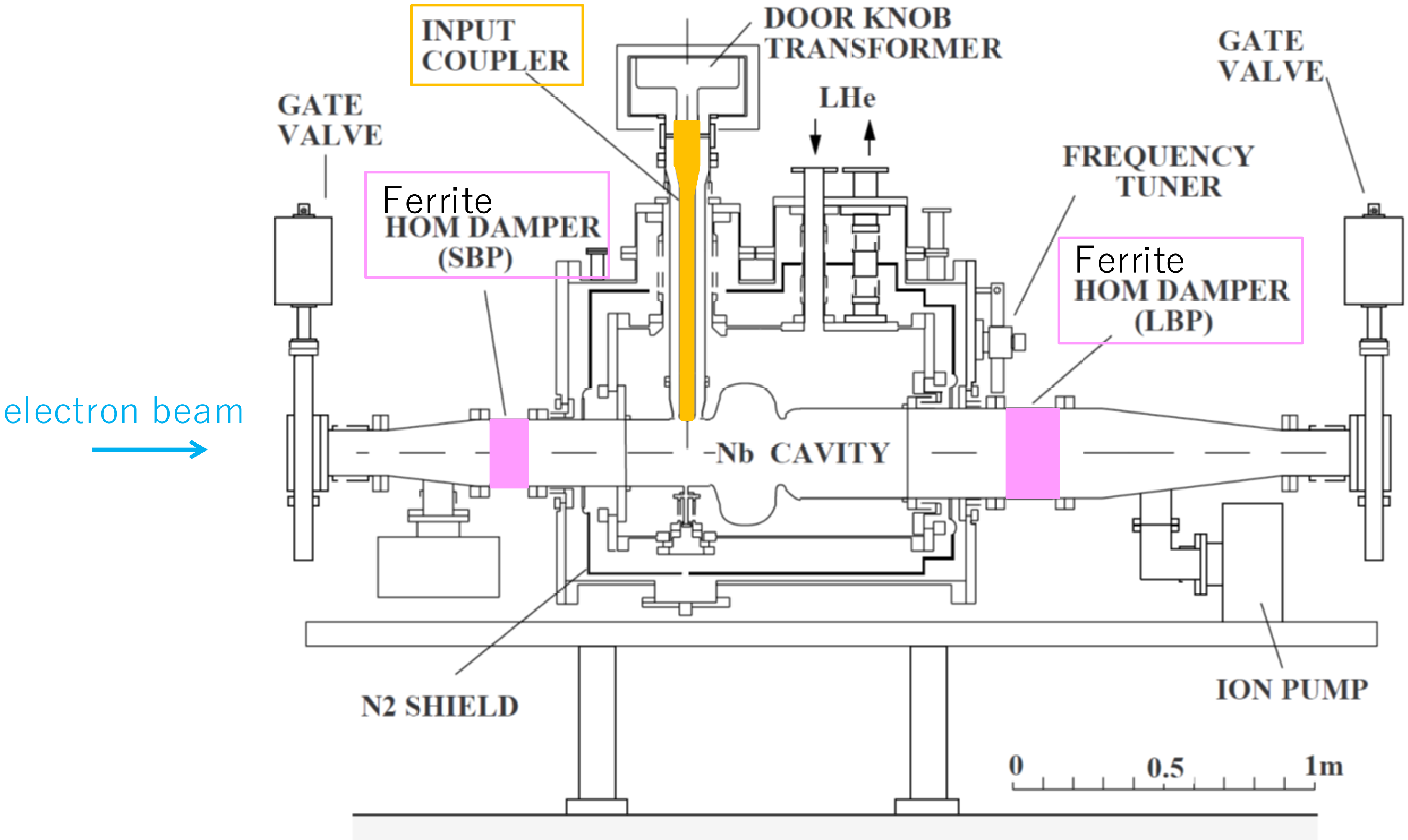
| Cavity Desing & Parameters in SuperKEKB | |
|---|---|
| Number of Cavities | 8 |
| Frequency | 509 MHz |
| Gap length | 243 mm |
| Accelerating Rsh/Q | 93 Ohm |
| Geometrical factor | 251 Ohm |
| Esp/Eacc | 1.84 |
| Hsp/Eacc | 4.03 mT/(MV/m ) |
| Max. Beam Current | 2.6 A |
| RF Voltage | 1.5 MV/cav. (~6 MV/m) |
| External Q | $5 \times 10^4$ |
| Unloaded Q at 2 MV | $1 \times 10^9$ |
| **Max. Beam Power** | **400 kW/cav.** |
| **Expected HOM Load** | **37 kW/cav.** |
| Static loss | 30-35 W/cav. |
| Total load/refrigerating capacity | 1.6 kW/8.1 kW |





SCC Modules in SuperKEKB Tunnel

# SCC module in SuperKEKB



# SCC module in SuperKEKB

- 509 MHz niobium single-cell HOM-damped cavity, 4.4 K operation
- 8 SCC modules in HER (electron ring) & one spare module
- SRF system is reused from KEKB including cryogenic system.
- **Beam power of SRF will be kept the same as at KEKB by applying phase-difference and sharing with ARES cavities.**
- Main challenges and Issues for SCC in SuperKEKB
  - **Large Beam Power**
    - 400-kW of input power is expected.
    - Careful adjustment of cavity phase difference
  - **Large HOM Power**
    - Due to twice high beam current and shorter bunch length
    - Reduction of the load of ferrite dampers is necessary.
    - Additional SiC HOM damper
    - Reinforcement of water-cooling capacity
    - Considering Build-up effect of HOM due to narrow bunch spacing
  - **Long-term Operation**
    - Degradation of cavity performance due to accidental and intentional vacuum works in over 20-years operation
    - Performance Recovery by Horizontal High-Pressure Rinse (HHPR)
    - SuperKEKB could operate for the next 10 or more years…

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|---|---|
| Number of Cavities | 8 |
| Frequency | 509 MHz |
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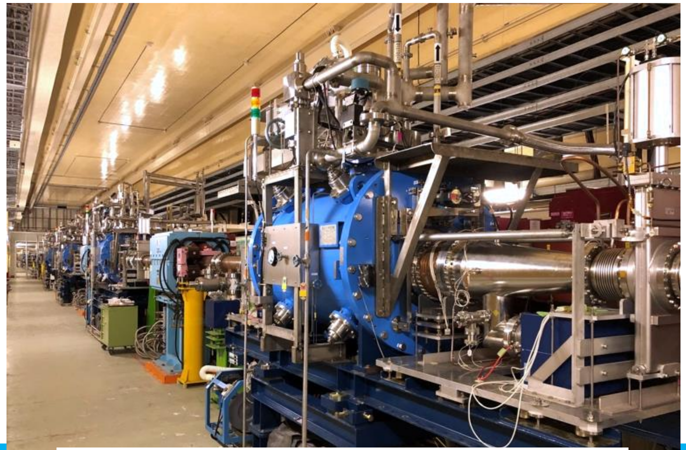
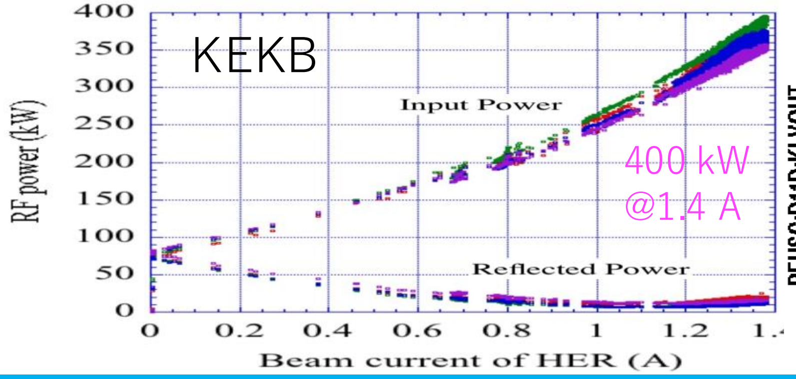
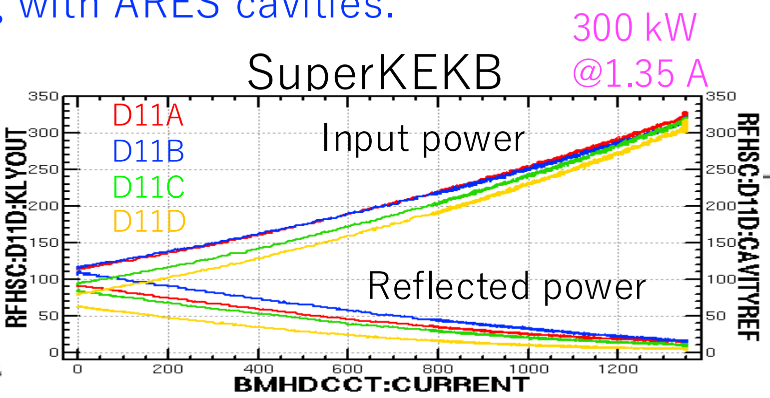


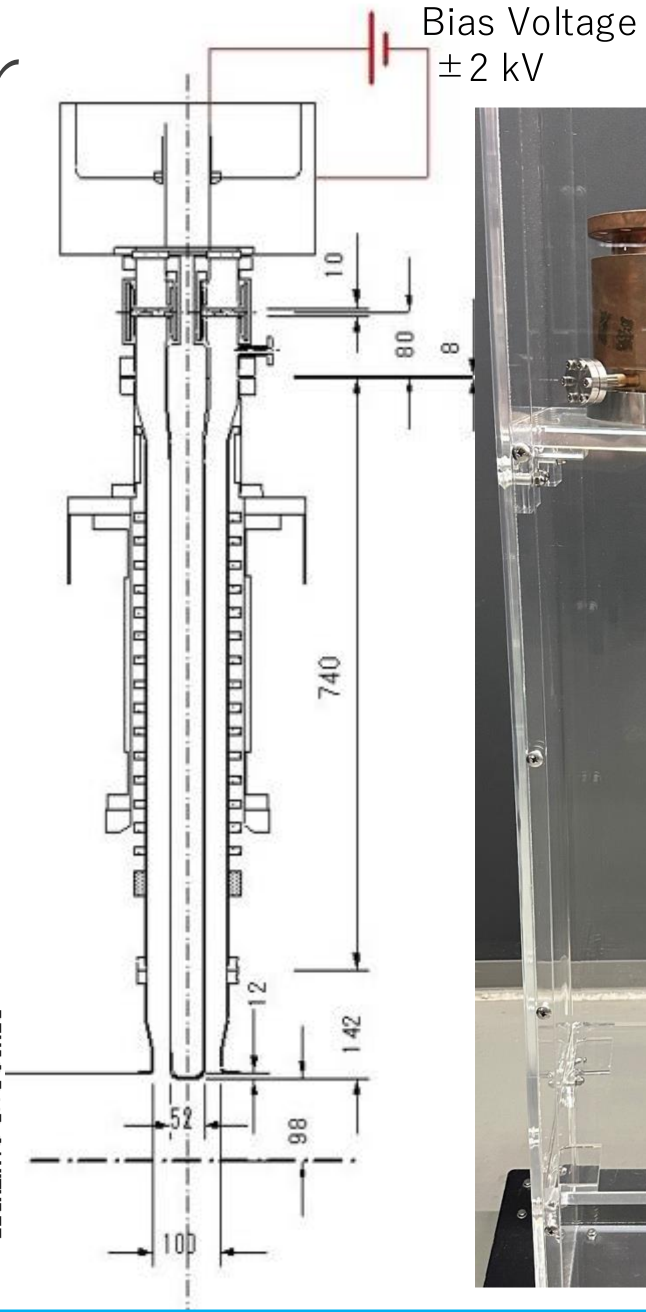
SCC Modules in SuperKEKB Tunnel

# High Power Input Coupler

- Coaxial antenna-type input coupler developed for KEKB based on TRISTAN
- Conditioned up to 800 kW in traveling wave mode in test stand
- Conditioned up to 300 kW in total reflection mode in cryomodule
  - KEKB design current : 1.1 A
  - Original $Q_{\mathrm{ext}} = 7 \times 10^4$ at 1.5 MV/cav. and $P_{\mathrm{beam}} = 240$ kW
  - The beam current was increased more than design current to achieve higher luminosity.
  - To increase the delivered beam power, $Q_{\mathrm{ext}}$ was lowered by using thinner gasket.
- $Q_{\mathrm{ext}} = 5 \times 10^4$, $P_{\mathrm{beam}} =$ **400 kW** at 1.4 A (achieved in KEKB)
- SuperKEKB : Design current 2.6 A
- No change of $Q_{\mathrm{ext}}$ to avoid contamination of cavity
- Beam power of SRF will be kept the same as at KEKB by applying phase-difference and sharing with ARES cavities.

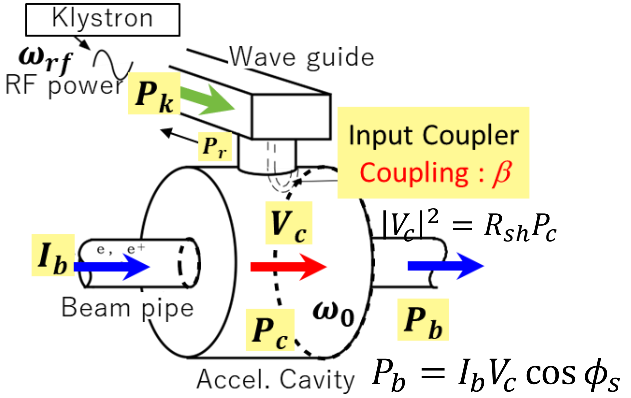


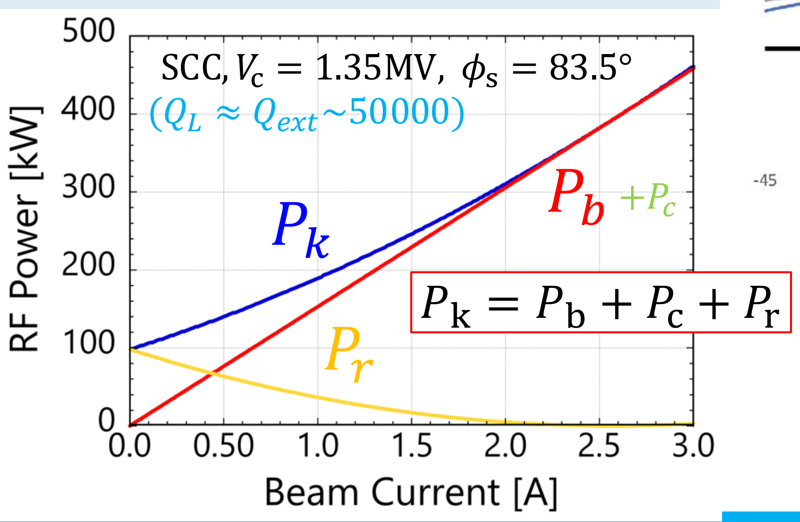

# Sharing beam power with ARES and SCC

## Schematic of Cavity Driving




$P_k$ : klystron output power, $P_r$ : reflection power,
$P_c$ : cavity wall loss

## Klystron Output Power vs Beam Current




Beam Power $P_b$ (=Providing Power to Beam) : $P_b = I_b V_c \cos\phi_{acc}$

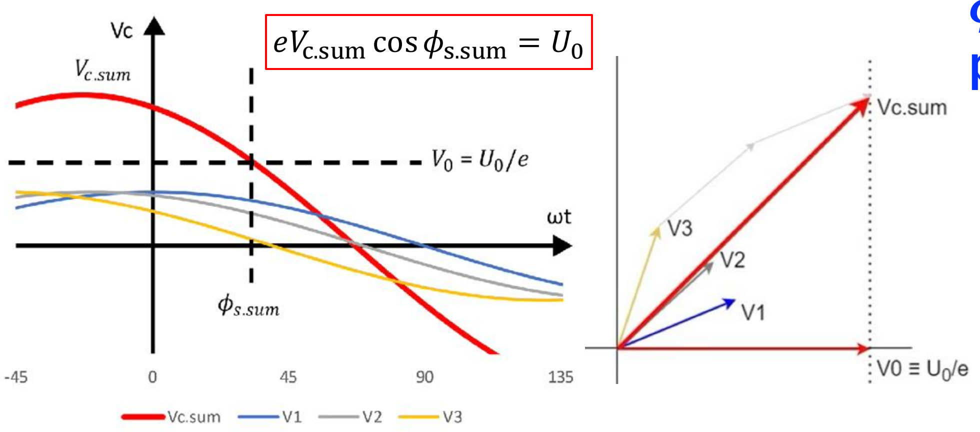
$I_b$ : ave. beam current, $V_c$ : each cavity voltage, $\phi_{acc}$ : acc. phase for each cavity

**Synchronous Phase ($\phi_{s.sum}$) is determined automatically by 1-turn loss ($U_0$) to balance with total acc. voltage ($V_{c.sum}$).**

$$eV_{c.sum}\cos\phi_{s.sum} = U_0$$

$V_{c.sum}$ : vector sum of all cavity voltages
$\phi_{s.sum}$ : synchronous phase for $V_{c.sum}$
$U_0$ : radiation loss in 1-turn

*ignoring parasitic loss, here




**$\phi_{acc}$ for each cavity depends on phase-difference among cavities.**

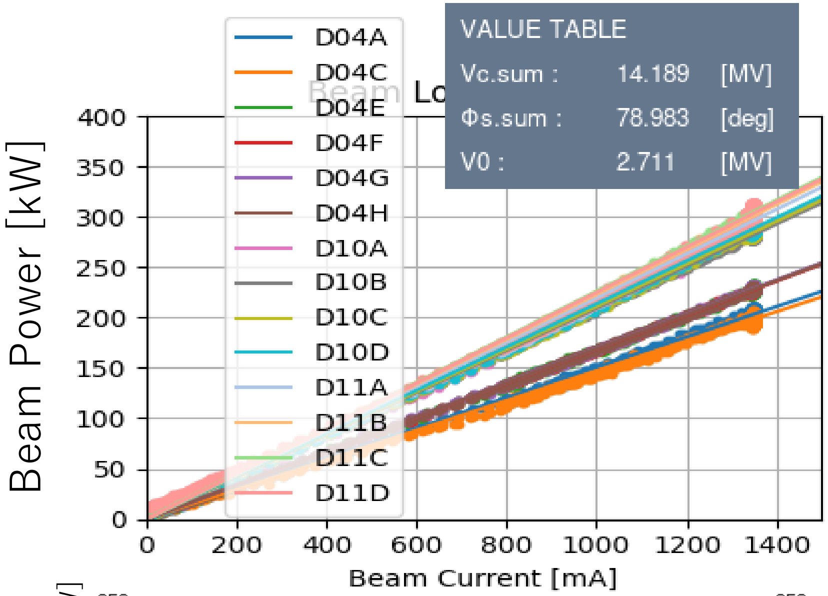
→ Required klystron output power ($P_k = P_b + P_c + P_r$) depends on the phase-difference.

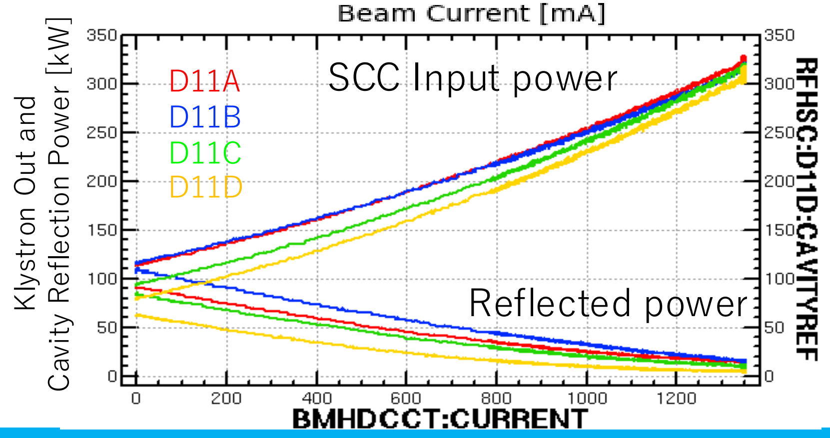
Klystron output power of ARES and SCC stations are limited by some reasons.

To share the large beam power among ARES and SCC stations to achieve design current, it is important to adjust $\phi_{acc}$ considering the difference between ARES and SCC station.

# Sharing beam power with ARES and SCC

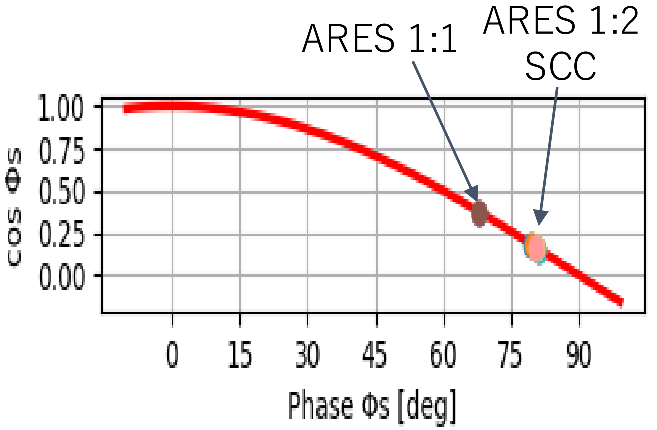
Present operation status of phase-difference between ARES and SCC




| | station | Vc[MV] | $\phi_{acc}$[deg] |
|---|---|---|---|
| ARES(1:2) | D04A | 0.80 | 79.19 |
| | D04C | 0.80 | 79.46 |
| ARES(1:1) | D04E | 0.45 | 67.96 |
| | D04F | 0.45 | 68.02 |
| | D04G | 0.45 | 67.89 |
| | D04H | 0.45 | 67.95 |
| SCC | D10A | 1.35 | 80.97 |
| | D10B | 1.35 | 81.13 |
| | D10C | 1.35 | 81.03 |
| | D10D | 1.35 | 80.92 |
| | D11A | 1.35 | 80.67 |
| | D11B | 1.35 | 80.52 |
| | D11C | 1.35 | 80.39 |
| | D11D | 1.35 | 80.44 |

acc. phase $\phi_{acc}$ for each station



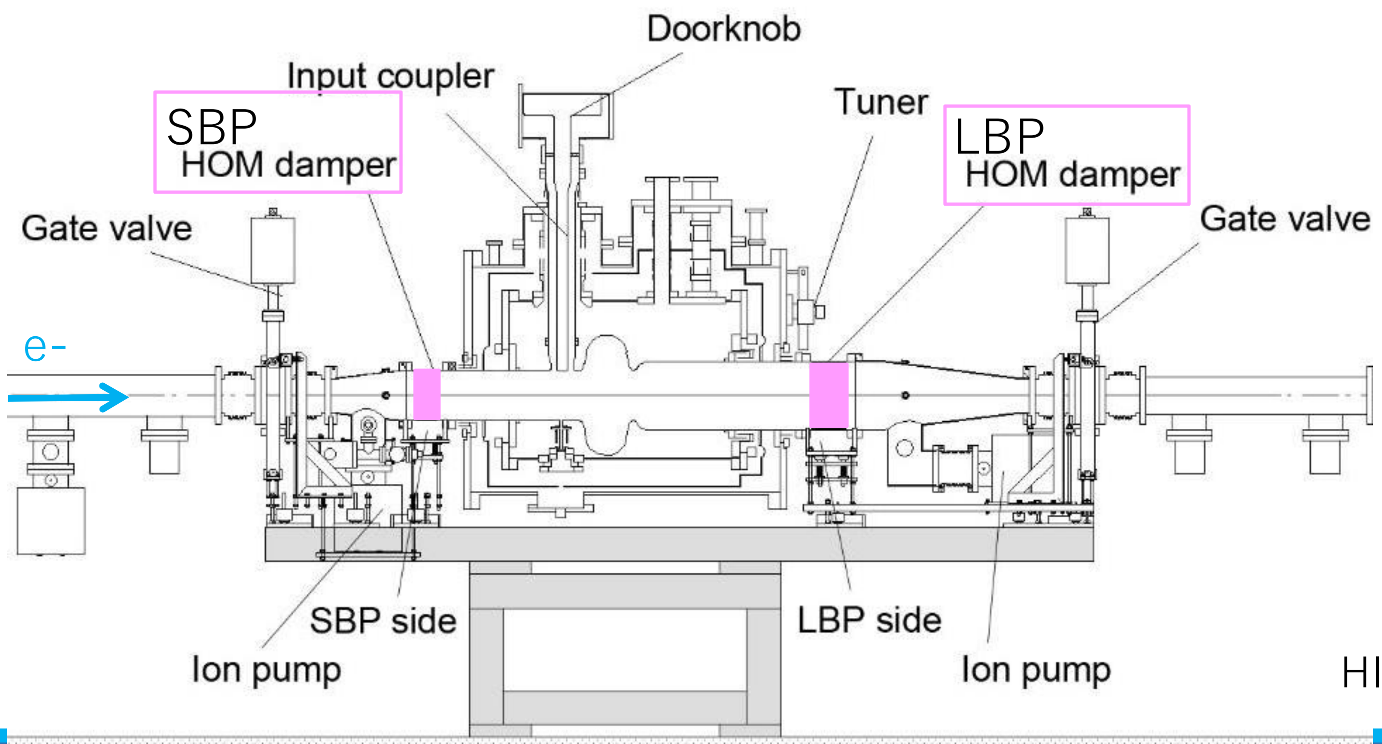

Cavity input power of SCC stations were maintained around 300 kW at 1.35 A by phase difference with ARES stations.

When the beam current increase more, we need to adjust the phase-difference carefully.

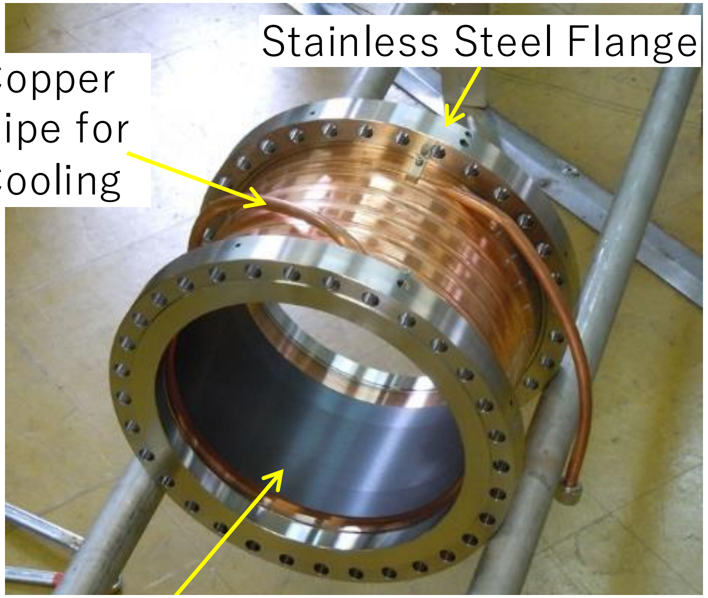
# Large HOM Power

# HOM-damped cavity structure with Ferrite damper

- HOMs can propagate toward beam pipes due to large aperture size.
- A Pair of Ferrite HOM dampers is installed outside of cryomodule.
  - ➢SBP damper : ϕ220 mm, t=4mm, L=120mm, LBP damper : ϕ300 mm, t=4mm, L=150mm
  - ➢Max. absorbed power in KEKB : **16 kW/cavity** (1.4 A, $\sigma_z$=6 mm, 10 nC/bunch)
  - ➢Expected HOM power is **over 30 kW/cavity** at SuperKEKB design current (2.6 A)




Ferrite HOM Damper

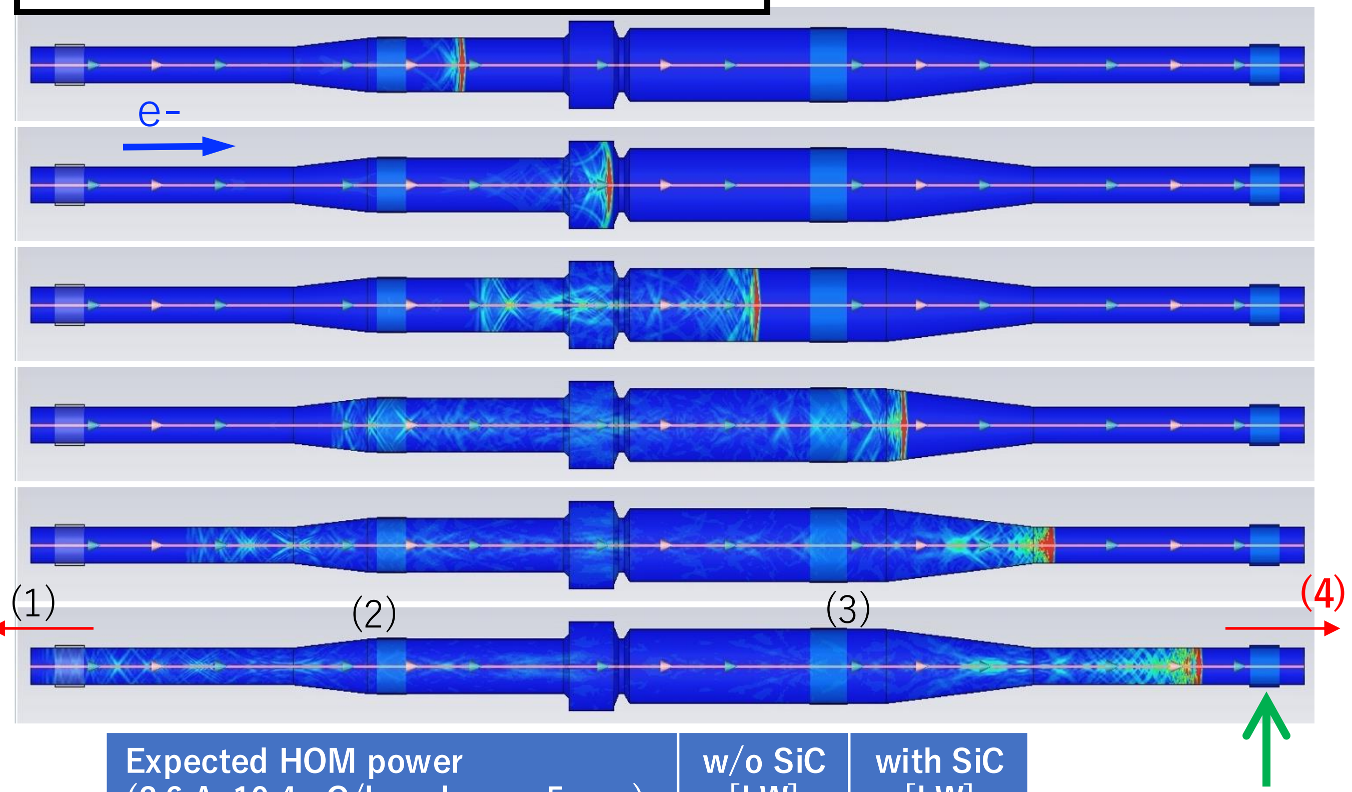



HIPped Ferrite (thickness: 4mm) on cupper duct

HIP : Hot Isostatic Pressing

# Study of HOM power for SuperKEKB

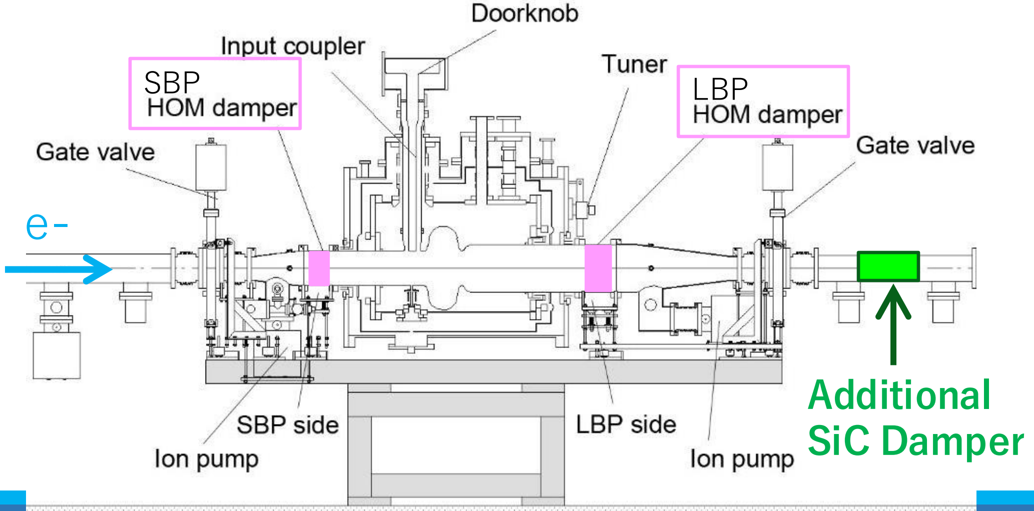
Wake field simulation using CST Particle Studio




| Expected HOM power (2.6 A, 10.4 nC/bunch, $\sigma_z$ = 5 mm) | w/o SiC [kW] | with SiC [kW] |
|---|---|---|
| (1) emit through upstream pipe | 1.3 | 1.4 |
| (2) absorbed by SBP ferrite damper | 8.7 | 9.5 |
| (3) absorbed by LBP ferrite damper | 11.8 | 12.8 |
| **(4) emit trough downstream pipe** | **15.4** → | **4.0** |

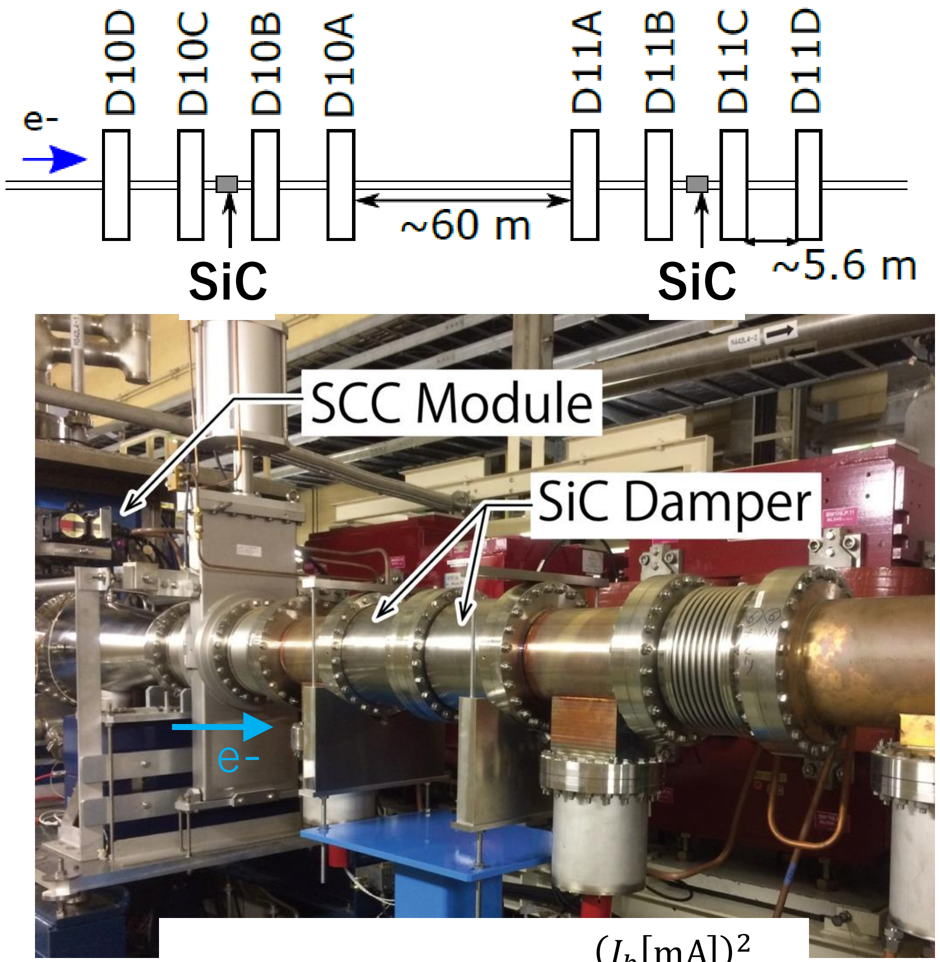
**Additional SiC Damper**

- Much HOM power emit through the downstream beam pipe.
- The emitted power becomes the additional load of the next cavity's ferrite dampers.
- **Additional SiC Damper is set at downstream of cavity.**
- The emission power is reduced to one-third in the simulation study.



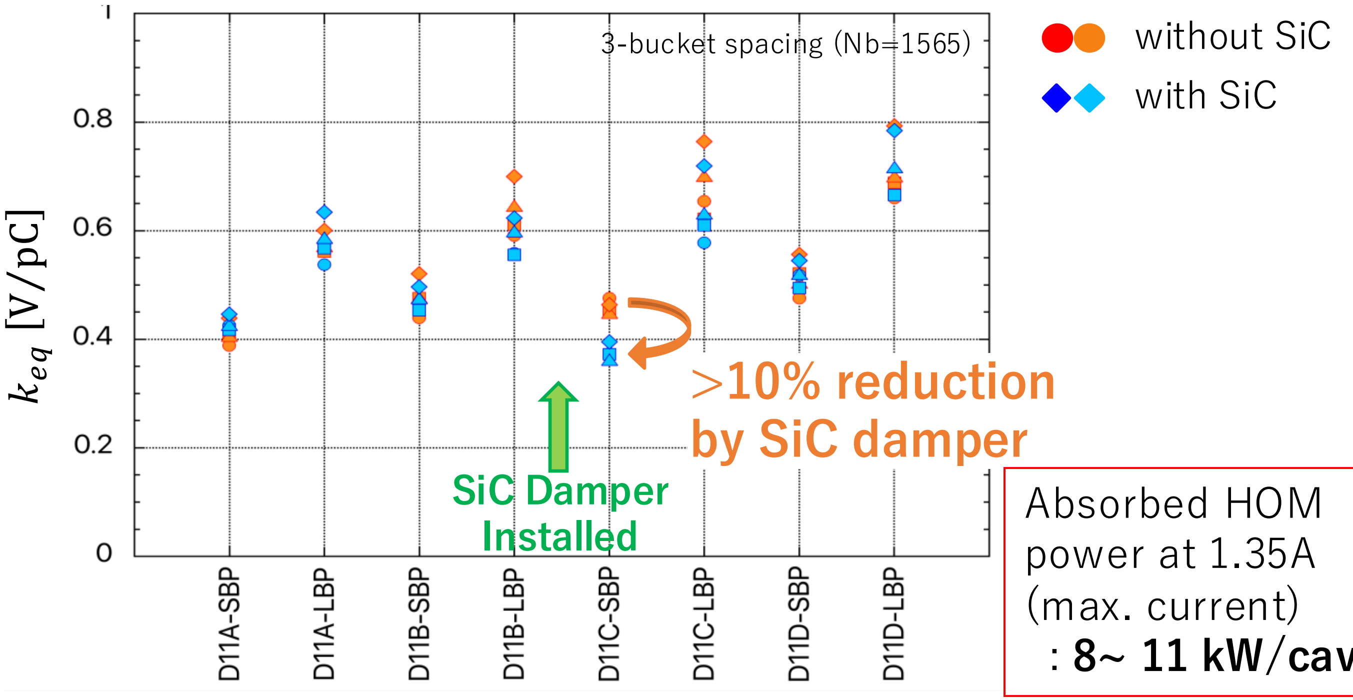
# Beam Operation with SiC Damper

## Layout of 8 SCCs and SiC dampers




$$P_{abs}[\mathrm{kW}] = k_{eq}\,[\mathrm{V/pC}]\frac{(I_b[\mathrm{mA}])^2}{N_b \cdot f_{rev}[\mathrm{kHz}]}$$

Equivalent LF of Ferrite dampers in D11 cavities




Absorbed HOM power at 1.35A (max. current) : **8~ 11 kW/cavity**

Two set of SiC dampers have been installed to SCC section. **The HOM power absorbed by the ferrite damper of downstream cavity (D11C-SBP in plot) was 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.

# Build-up Effect of HOM

T.Okada

| HOM Freq. (MHz) | $k_a$ | $\|F\|$ (2-bs) | $\|F\|$ (3-bs) |
|---|---|---|---|
| 782 | 0.00036 | 2 | 0.19 |
| 834 | 0.00042 | 0.42 | 1.8 |
| 918 | 0.0017 | 0.18 | 0.15 |
| 1002 | 0.009 | 2 | 1.4 |
| 1018 | 0.019 | 13.5 | 9 |
| 1032 | 0.0024 | 1.1 | 0.81 |
| 1065 | 0.0021 | 0.76 | 0.42 |

SBP cut-off freq.

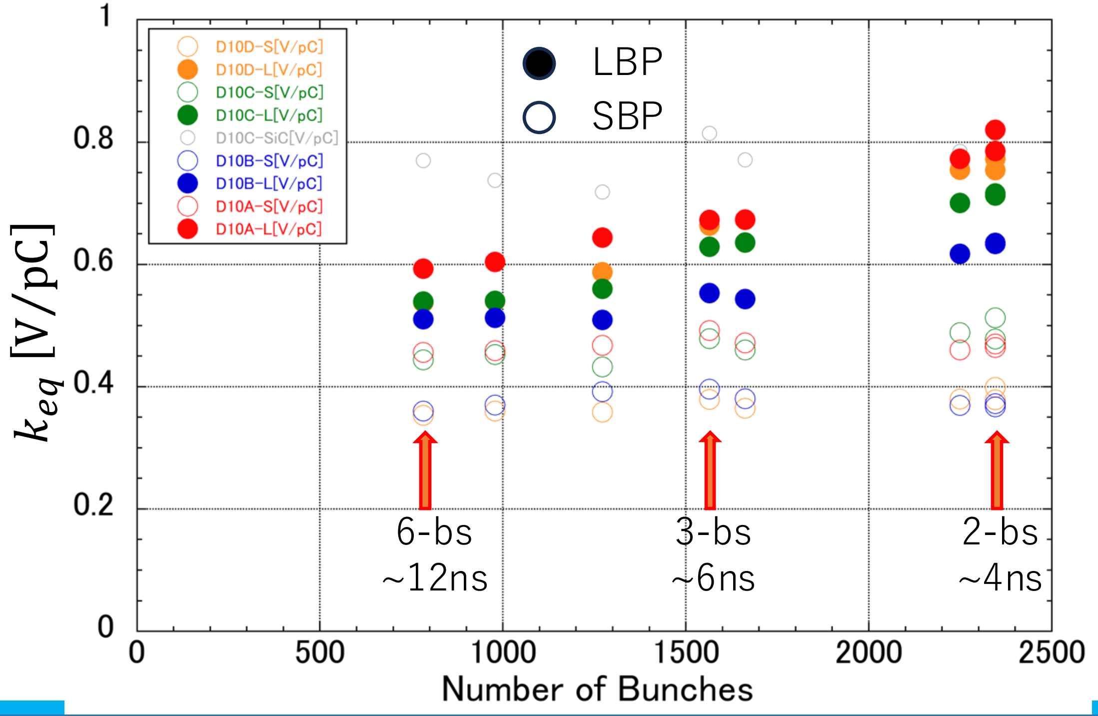
- In recent beam operation, bunch spacing dependence has been observed in the absorbed power in LBP ferrite dampers.
- Power dissipation depend on absolute value of a function $F$, named Build-up factor.

$$V_{\mathrm{b}} = \sum_n V_{\mathrm{b0}} \mathrm{e}^{(\mathrm{i}\delta-\tau)\mathrm{n}} = V_{\mathrm{b0}}(F_{\mathrm{R}} + \mathrm{i}F_{\mathrm{I}}),$$

$$F = \frac{1-\mathrm{e}^{-2\tau}}{2\,(1-2\mathrm{e}^{-\tau}\cos\delta+\mathrm{e}^{-2\tau})} + \mathrm{i}\frac{2\mathrm{e}^{-2\tau}\sin\delta}{2\,(1-2\mathrm{e}^{-\tau}\cos\delta+\mathrm{e}^{-2\tau})}$$

- The build-up factor $F$ can explain difference of equivalent loss factor $k_{eq}$ of each HOM damper between 3-bucket and 2-bucket spacing (bs) operation.
  - There are some dampers that show more build-up than expected.
- Investigation of Build-up effect is on going with both measurements and calculations.

$$P_{abs}[\mathrm{kW}] = k_{eq}\,[\mathrm{V/pC}]\,\frac{(I_b[\mathrm{mA}])^2}{N_b \cdot f_{rev}[\mathrm{kHz}]}$$



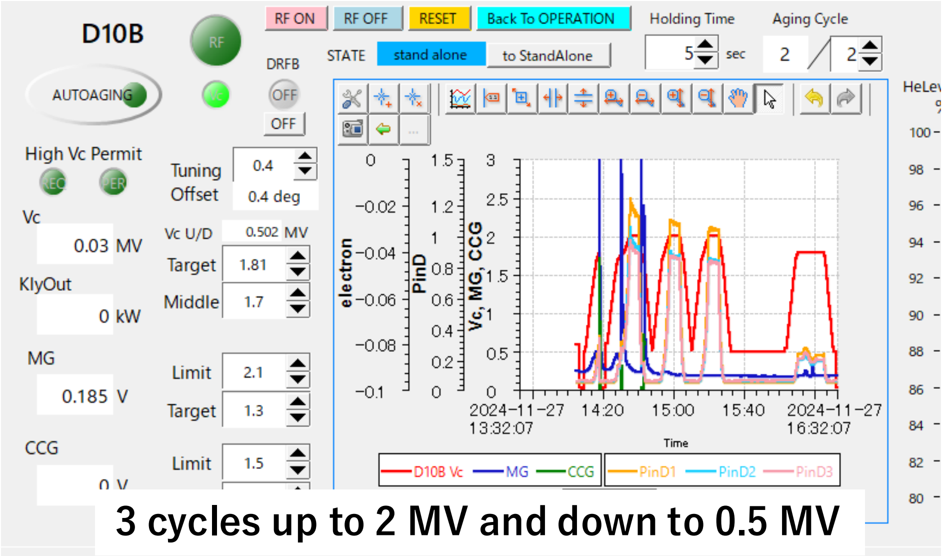
# Operation Status of SRF system

# Operation Statistics of SRF System

## Usual Operation of Cavity

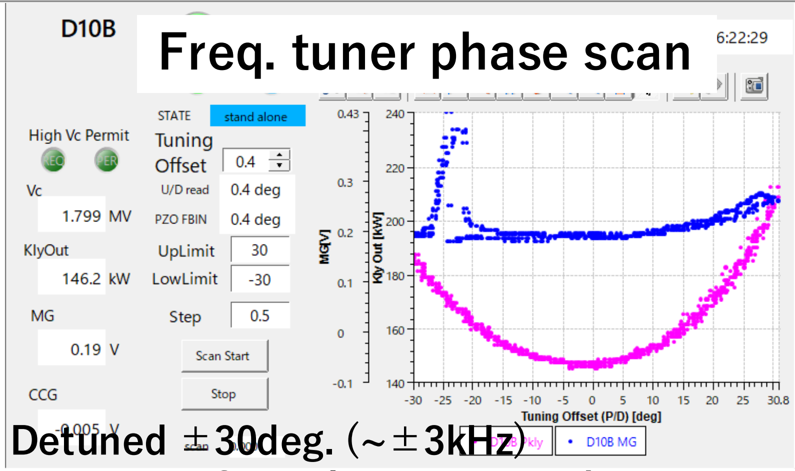
- **Warming up to room temperature twice a year**
  - Beam operation (Physics Run) : 6~7 months/year with summer and winter shutdown
    - Planning no winter shutdown
  - Safety inspection of cryogenics; pressure gauge, safety valve, etc
  - Cavity free from frequency tuner during warming up and cooling down
  - **Coupler conditioning with bias voltage before cooling (not automated)**
- **Cool-down speed : 2.5K/hour**
- **$Q_0$ measurement before (and after) beam operation**
  - Understanding the cavity performance
- **Regular maintenance day (8 hours) of every 4 weeks**
  - Intervals have been expanded from 2 to 4 weeks to ensure beam operation time in 2024.
  - Visual inspections
  - **Cavity conditioning (Automated aging)**

**Automated cavity aging**




**3 cycles up to 2 MV and down to 0.5 MV**

**Freq. tuner phase scan**




**Detuned ±30deg. (~±3kHz)**
**Degusing of coupler is expected.**

# Operation Statistics of SRF System

In SuperKEKB, the beam is aborted several times in a day by some interlock alarm.

➢ **Beam Aborts caused by SRF system is not often.**

- Collect signals of RF, beam, beam loss monitors, etc to find the last message from the beam and to know the true cause of each beam abort
- No effect of the long interval of regular maintenance day for the MTBF (Mean Time Between Failures), so far.

- **Multipacting (MP) breakdown of Cavity**
- **Electric breakdown of Piezo actuator for freq. tuner**
  - Insulation failure due to humidity was fixed by using desiccant.
  - Recently breakdown without precursory occur.
  - Cavity can be operated without piezo by changing tuner control settings. Recovered in 30 min.

◆ 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 (gear mechanism, 2022) : Beam operation was suspended for 3 hours to replace the tuner.

excluding due to LLRF and HPRF

| Beam Aborts caused by | Recovery time | 2019 | 2020 | 2021 | 2022 | 2024 |
|---|---|---|---|---|---|---|
| MP in Cavity | 2-3 min. | 2 | 2 | 12 | 7 | 8 |
| Piezo breakdown | < 1 hour | 6 | 5 | 1 | 0 | 5 |
| Chiller failure | < 1 hour | 1 | 1 | 3 | 0 | 0 |
| Others | | 0 | 0 | 2 | 2 | 3 |
| Total | | 9 | 8 | 18 | 9 | 16 |
| Trip Rate [/day/8 cavities] | | 0.06 | 0.04 | 0.09 | 0.07 | 0.07 |
| **MTBF [days/8 cavities]** | | **16.5** | **22.5** | **10.9** | **13.4** | **14.6** |
| Operation days | | 149 | 180 | 196 | 121 | 233 |
| Total number of beam aborts (>50mA, including LER single) *except injection tuning | | - | ~650* | ~1100 | ~730 | ~1800 |

**SRF system is stable even in >1-A beam operation.**

# Summary

- SuperKEKB is steadily increasing the beam current and continues to update own luminosity record.
- SuperKEKB is a challenging machine for SRF system because of its large beam power, large HOM power and long-term operation.
- Maximum beam power delivered by SCC was 400 kW in KEKB operation. Beam power of SRF system will be kept the same as at KEKB by applying phase-difference and sharing with ARES cavities.
- 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. More evaluations of Build-up effect are important.
- SRF system is operating stably with low trip rate at large beam currents of 1.35 A for HER so far.

# Thank you for your attention.

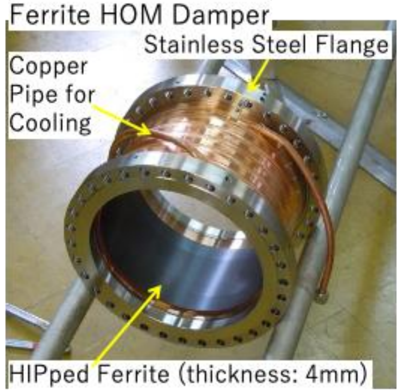
# Back-up

- HOM power limits the Beam Current
- Instabilities due to Accelerating Mode
  - Coupled Bunch Instability (CBI) related to m=-1, -2 and -3 modes
  - Static Robinson Instability (zero-mode)
- High Power RF system
- Cryogenic system

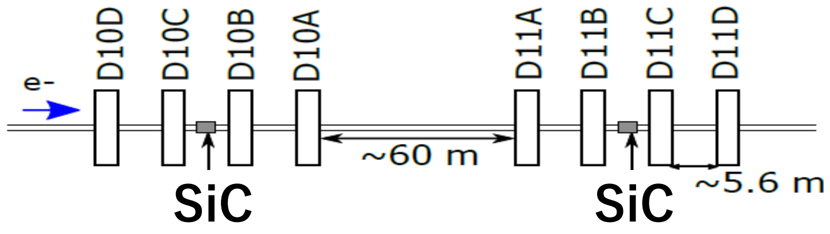
# HOM power can limit the beam current

## Limits of ferrite dampers

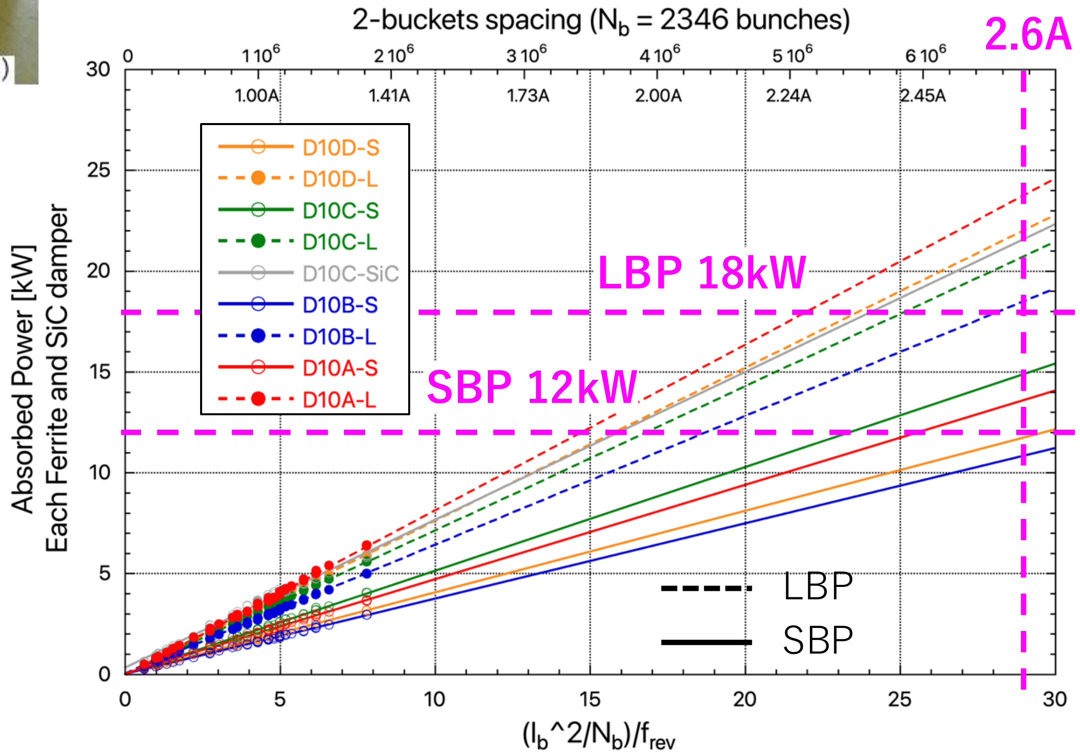
- Temperature of copper duct ≦ 60°C
  - The ferrite is HIPped on copper duct.
  - To prevent ferrite cracking
- Water flow speed (flow rate) ≦ 8 L/min
  - To avoid the erosion-corrosion of cooling pipe




→ 12 kW for SBP
18 kW for LBP




**Installation of additional SiC dampers are expected to reduce the load on downstream ferrite dampers.**




More R&D

- Build-up Effect depending on bunch spacing
- Effect of crack of ferrite
- Improvement of the cooling capacity
- Monitoring erosion-corrosion (Can we increase the flow rate?)
- etc…

# Estimation of Growth Rate of CBI due to Acc. Mode

T.Kobayashi

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

**Cavity Detuning (optimum tuning) $\Delta f_a$@ Design Current**

**ARES : $\Delta f_a$ ~ -28 kHz (for $\pi/2$ mode)**

**SCC : $\Delta f_a$ ~ -44 kHz**

**$|\Delta f_a|$ < revolution freq. $f_{rev}$ ~ 100 kHz**

By optimum tuning, cavity resonant frequency is detuned to lower side of $f_{rf}$.

**Growth Rate of mode $\mu$ : $\tau_\mu^{-1}$**

$$\frac{1}{\tau_\mu} = AI_b \sum_{p=0}^{\infty} \left\{ f_p^{(\mu+)} \mathrm{Re}\,Z\left(f_p^{(\mu+)}\right) - f_p^{(\mu-)} \mathrm{Re}\,Z\left(f_p^{(\mu-)}\right) \right\}$$

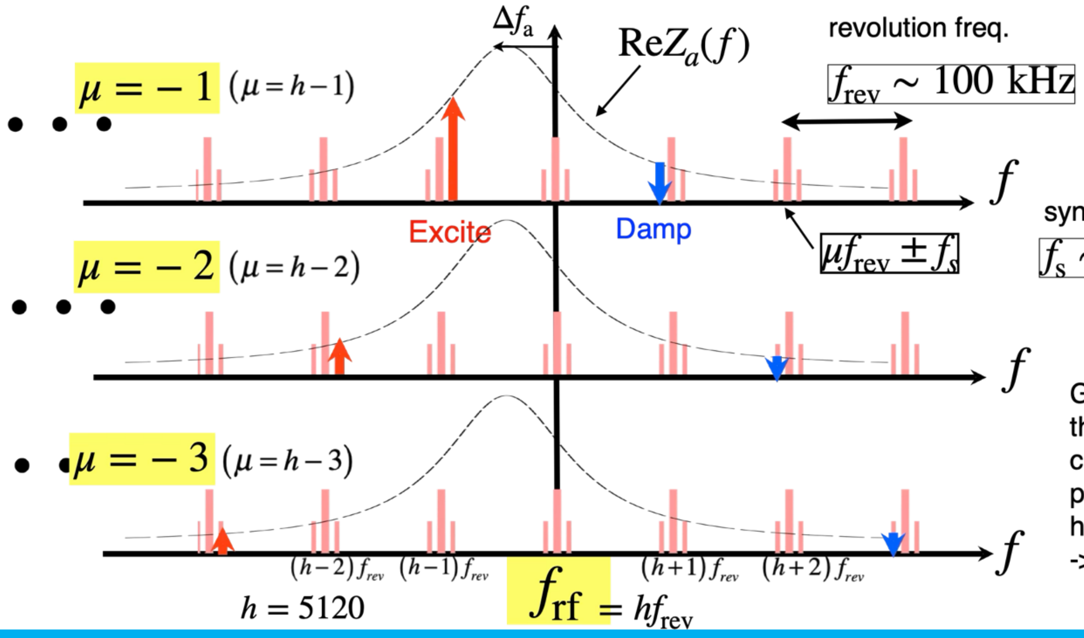
exciting term / damping term

$$A = \frac{e\alpha_p}{2E_0 T_{rev} f_s}$$

$$f_p^{(\mu+)} = phf_{rev} + \mu f_{rev} + f_s$$

$$f_p^{(\mu-)} = (p+1)hf_{rev} - \mu f_{rev} - f_s$$

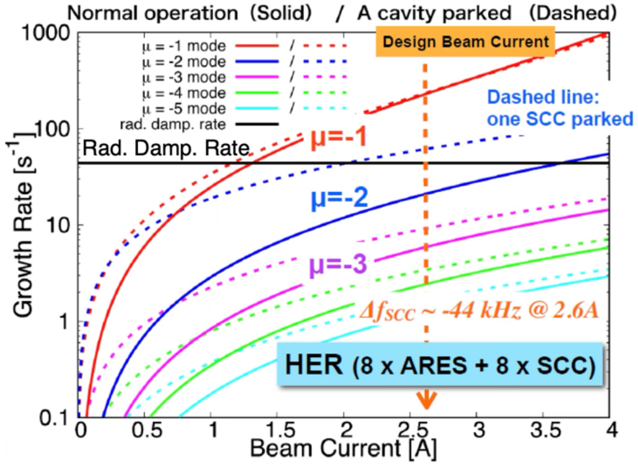
**Beam Spectrum with CBI Exciting↑ / Damping ↓ Effect**

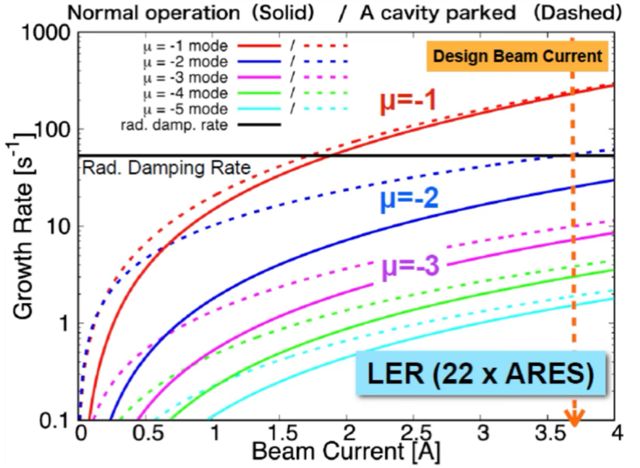



synchrotron osc. freq.

$f_s$ ~ 2.5 kHz

**Estimation Growth Rate of CBI due to Acc. Mode**



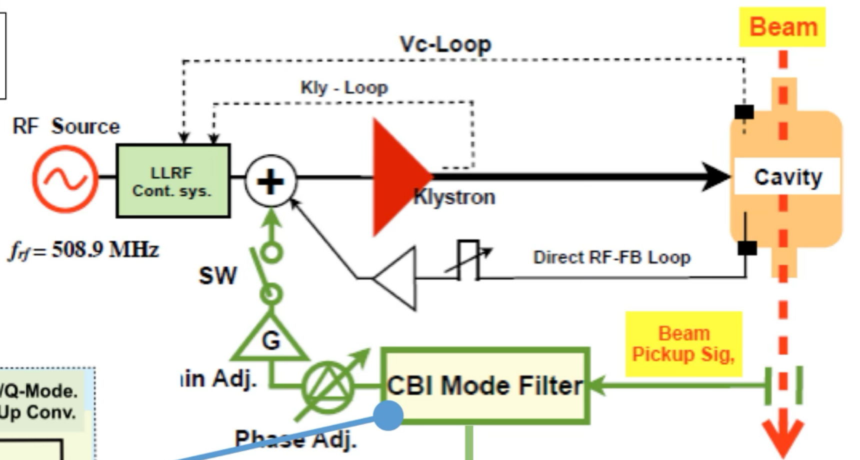

Growth rate of μ=-1 mode exceeds the damping rate for the design current. And when there are parked cavities, μ=-2 mode also has no margin.
-> CBI damper system is required.

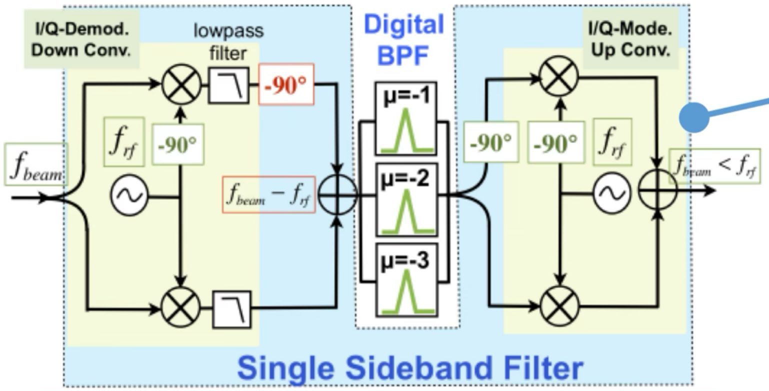
# Acc.-Mode CBI damper for SuperKEKB

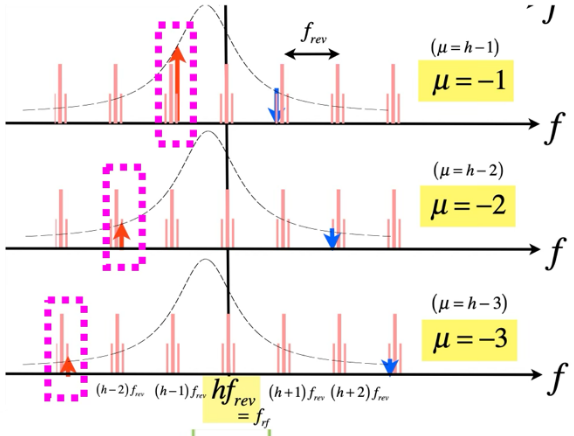
T.Kobayashi

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

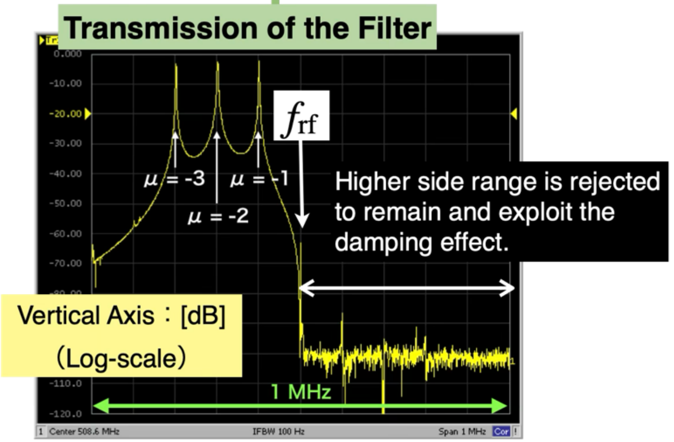
The CBI mode filter with digital BPF can transmit the frequencies of μ =-1, -2 and -3 modes in parallel.

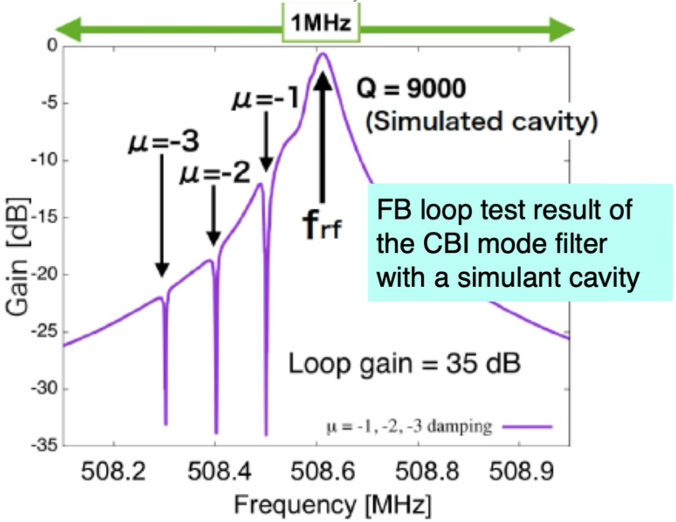



**Each mode frequency is extracted by each corresponding digital BPF. And loop phase and gain are adjusted by the digital BPF for each mode, independently.**



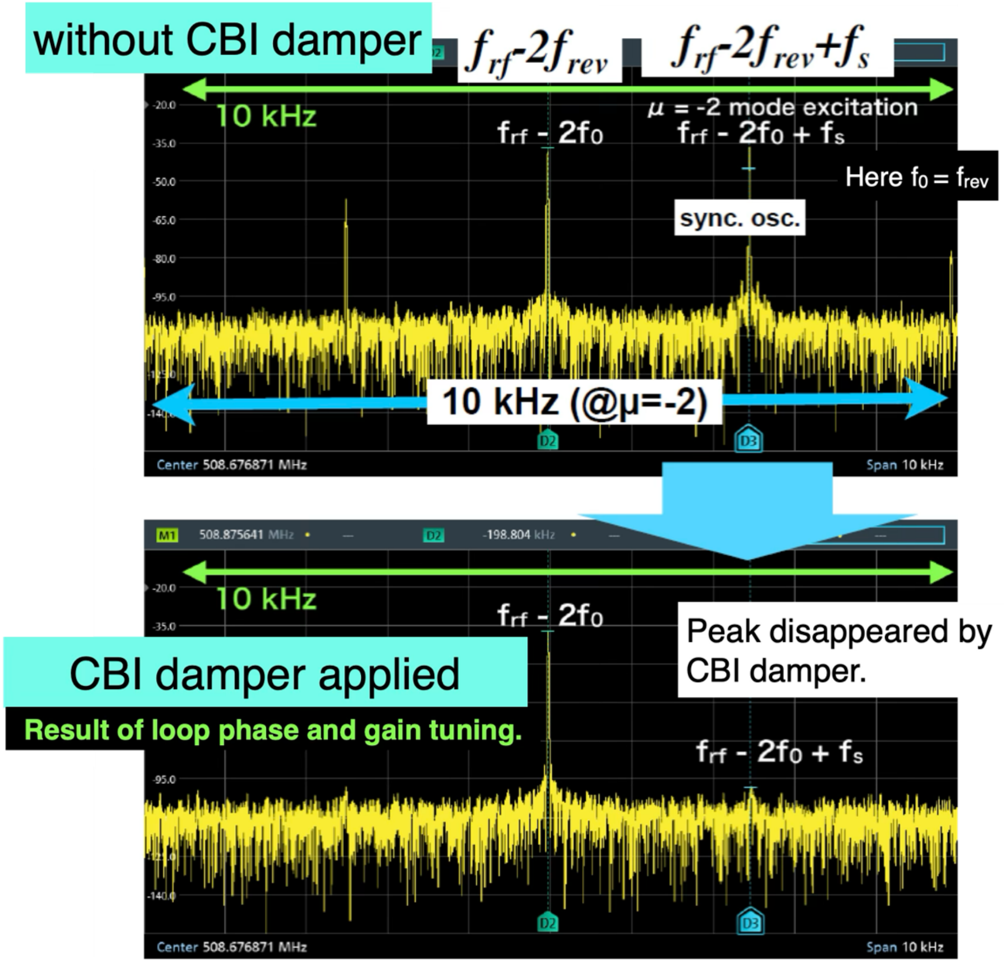

Impedance correspond μ =-1, -2 and -3 modes are suppressed successfully.

**Our klystron band width is narrow : ~ 130 kHz, while revolution frequency is ~ 100 kHz.**
**=> phase and gain property are not flat in the range of these CBI modes ( -1, -2, -3 mode).**
**=> Phase and gain should be tunable for each mode independently.**
**=> We had developed a parallel comb filter by using digital BPF for the CBI damper.** **(normal comb filter is not available for our case)**

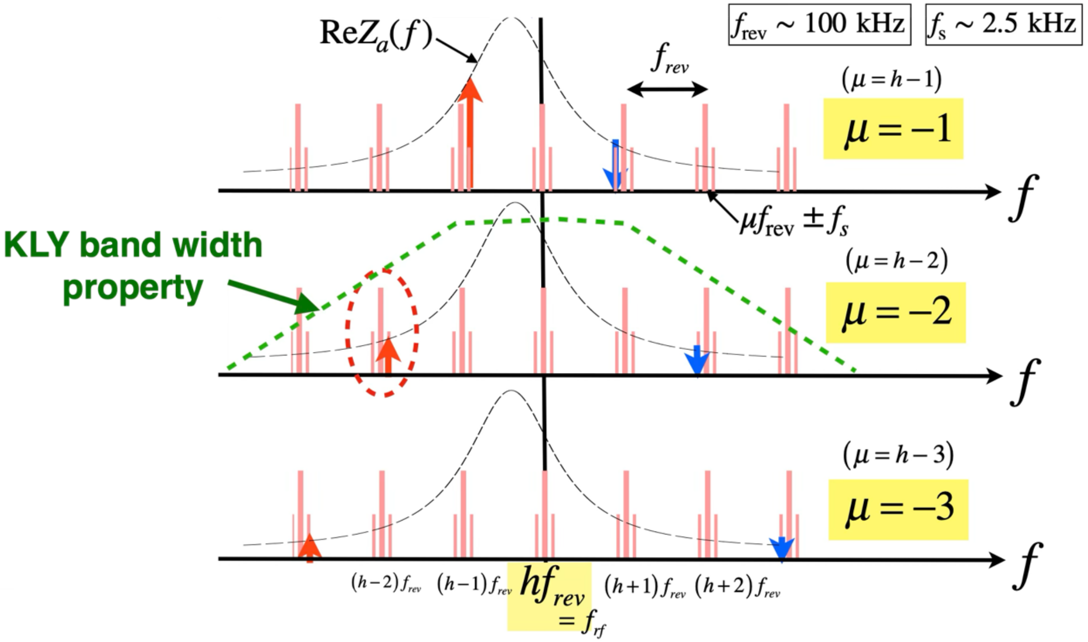
# Example of CBI Suppression by the Damper

T.Kobayashi

μ=-2 mode was excited purposely by large detuning of SCC for the damper test.




**Our klystron band width is narrow ( ~ 130 kHz) in comparison with $f_{rev}$, phase and gain are needed to be tunable for each mode independently. These can be adjusted by the digital BPF for each mode.**




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

In the present state, CBI is not a problem with this damper systems in beam operation so far.
($I_{b.max}$ : 1.6 A for LER and 1.4 A for HER)

K.Akai, PRAB **25**, 102002 (2022).
T.Yamaguchi et al., PRAB **26**, 044401 (2023).

# Instability due to Coherent Bunch Oscillation



This is another type of longitudinal instability related to the accelerating mode.
This instability arises from the **coherent synchrotron oscillation** where all bunches oscillate in the **same phase (zero-mode)**.
This instability limits the maximum beam current stored in high-current ring accelerators.

**Coherent oscillation (zero-mode)**

↓

$\boldsymbol{V_b}$ shifts with the bunch phase
No contribution for restoring force

↓

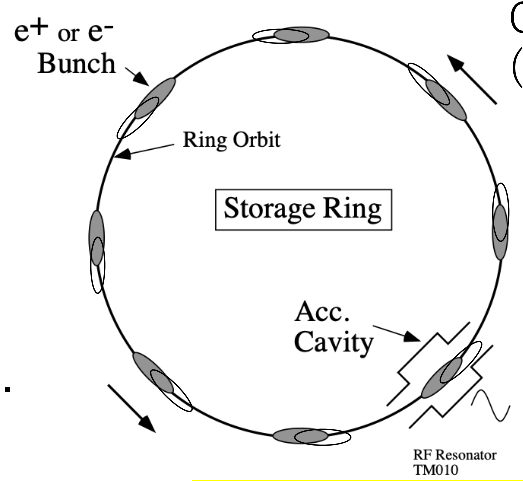
Only $\boldsymbol{V_k}$ contributes to the restoring force.
$\boldsymbol{\theta_k}$ is considered as the synchronous phase.

Restoring force decreases and synchrotron frequency decreases.

When $\omega_s \to \omega_s'$,

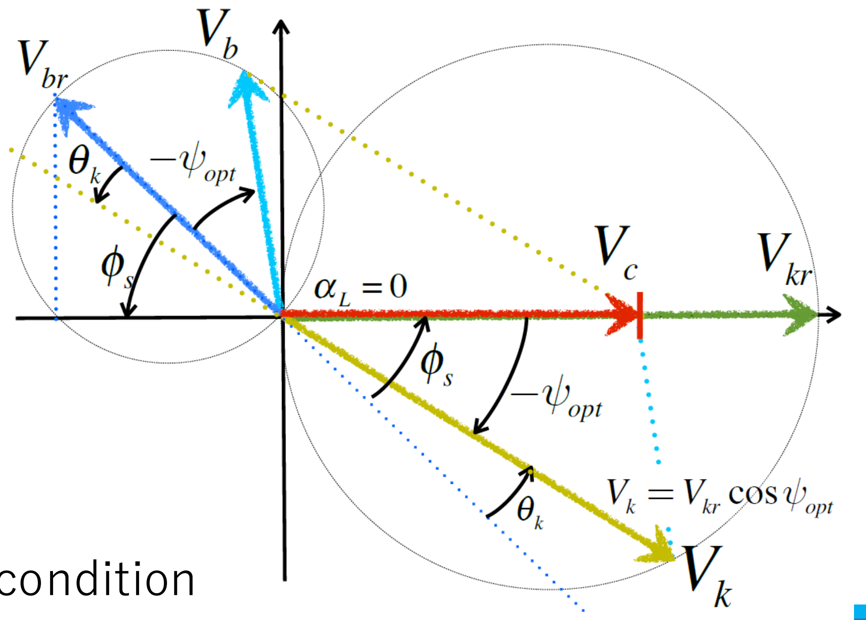
$$\left(\frac{\omega_s'}{\omega_s}\right)^2 = \frac{V_k \sin\theta_k}{V_c \sin\phi_s} = \frac{V_{kr}\cos\psi_{opt}\sin(\phi_s+\psi_{opt})}{V_c \sin\phi_s}$$

$$= \frac{1-\{(V_{br}/V_c)\cos\phi_s\}^2}{1+\{(V_{br}/V_c)\sin\phi_s\}^2}$$




Coherent synchrotron oscillation
(all bunches oscillate in the same phase)

Principle of phase stability dose not work.




$\omega_s' > 0$ ⇒

**Stable condition**

$$V_{br}\cos\phi_s < V_c$$

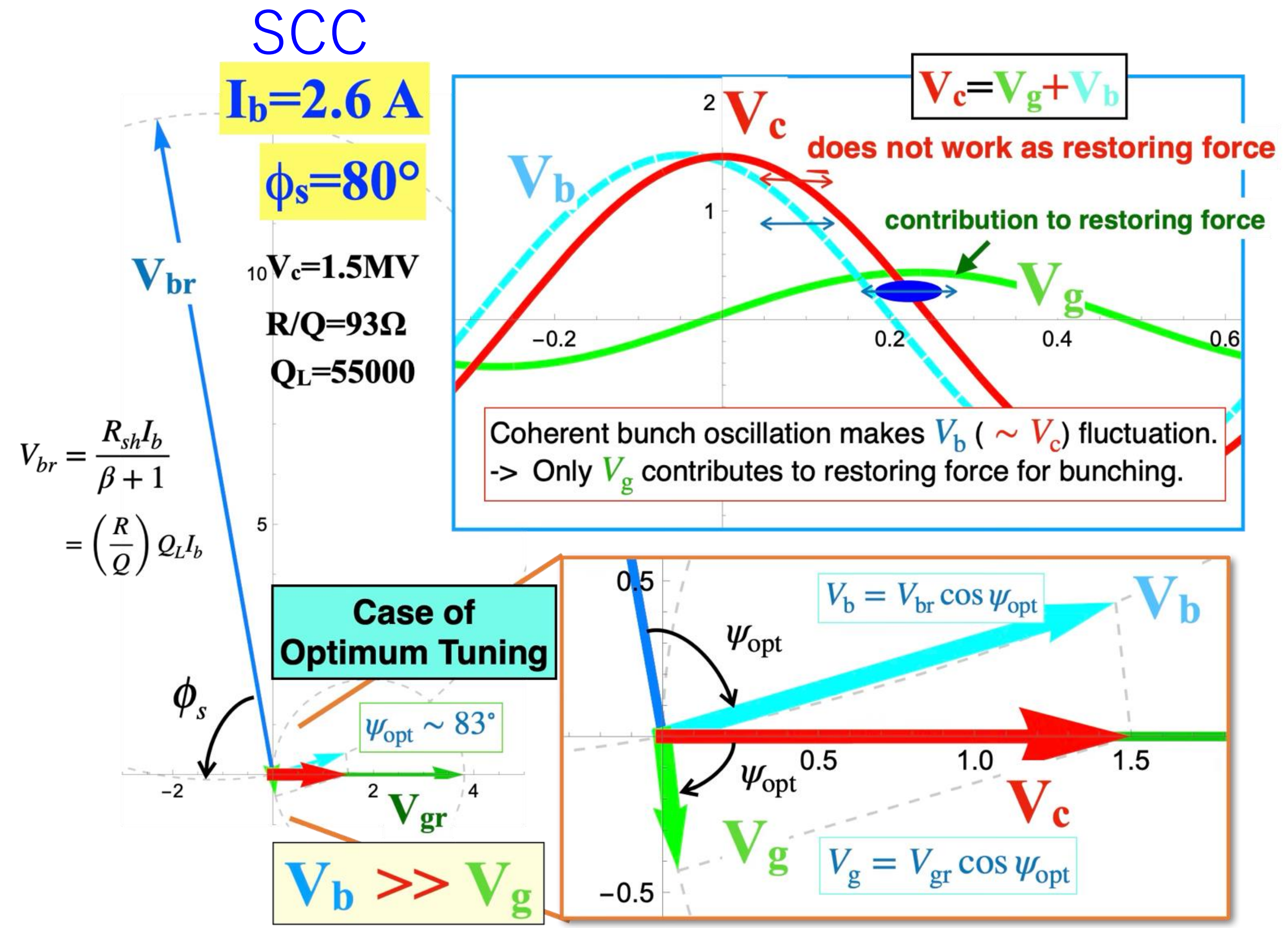
$$\frac{P_b}{P_c} < \beta + 1$$

satisfied in the optimum coupling condition

# Instability due to Coherent Bunch Oscillation

T.Kobayashi

In our case, this problem is more severe in HER **because SCC makes high beam induce voltage**.




$V_c = V_g + V_b$

Generator(KLY) Driving — Beam Exciting

**All bunches oscillate coherently (in zero-mode)**

**$V_b$ also fluctuates with the bunch oscillation**

**-> $V_c$ also fluctuates with the bunch oscillation,**

since $V_c$ almost consists of $V_b$ at the high current.

**$V_c$ losses contribution to restoring force for synchrotron oscillation.**

**-> Only $V_g$ contributes to the restoring force.**

**The principle of phase stability does not work enough.**

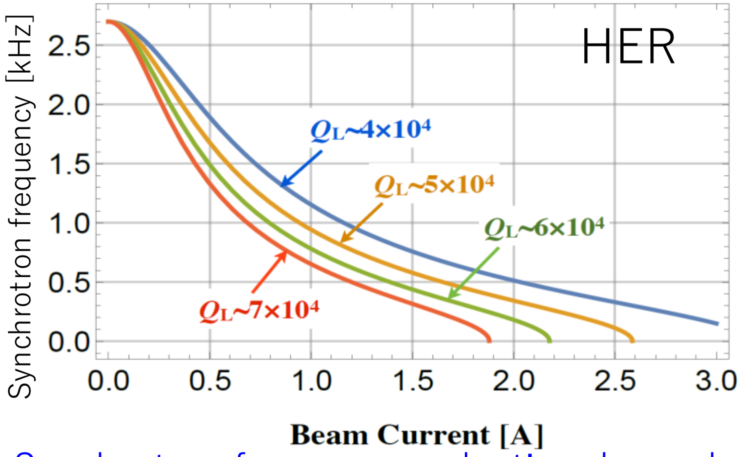
This kind of instability is frequently called

**Static Robinson Instability (SRI)**

# Static Robinson Instability in SuperKEKB

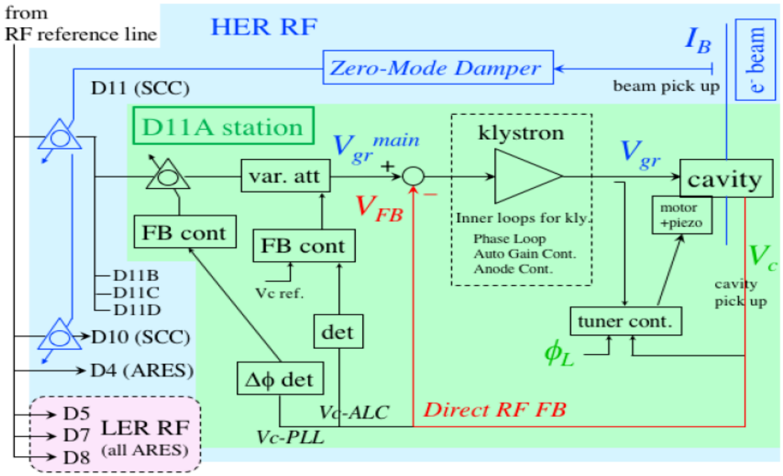
- In SuperKEKB, static Robinson instability is expected in the high current operation.
- In the beam operation, there are FB system called Direct RF feedback (DRFB) and Zero-mode damper (ZMD).

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



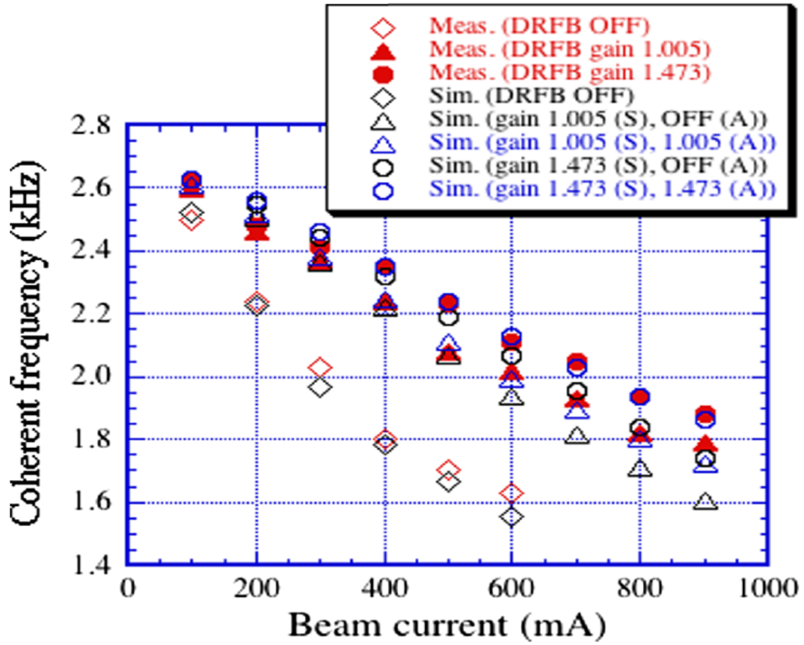

Synchrotron frequency reduction depends on $Q_L$. But, changing $Q_L$ of SCC should be avoided due to the need for vacuum work and the risk of surface contamination.

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 and different FB gains**

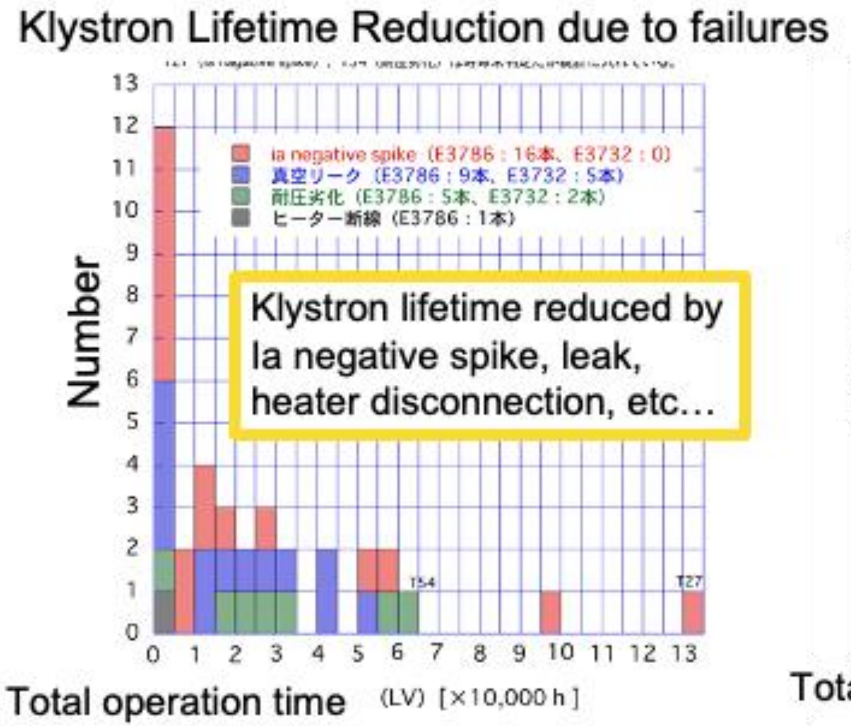


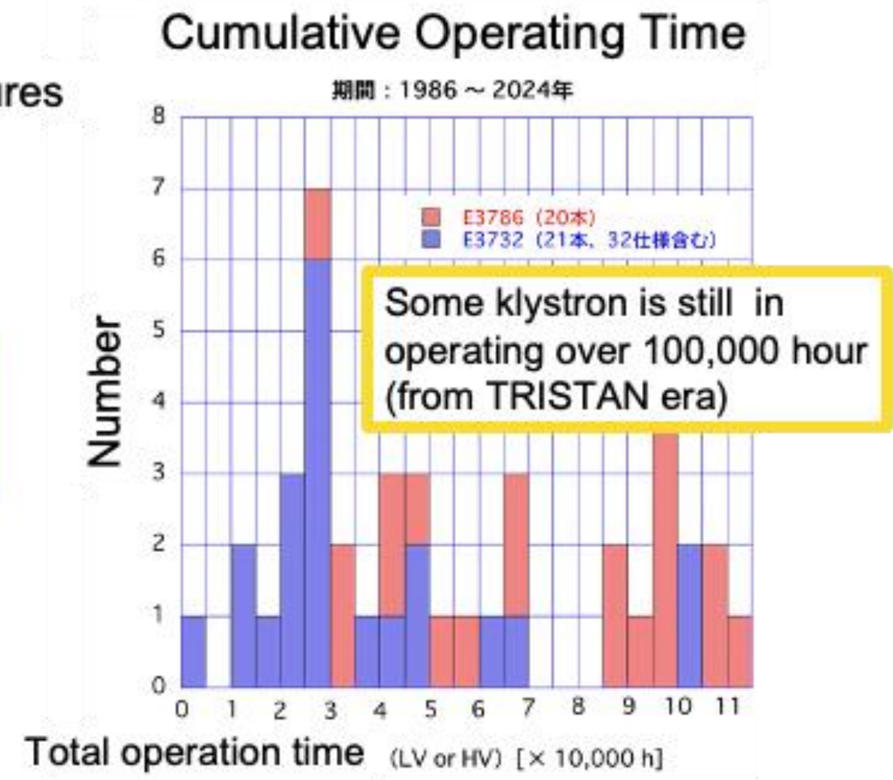

- ◆ The higher beam current can be stored stably by DRFB and ZMD in beam study.
- ◆ There is no discrepancy between the quantitative analysis and the beam study results.
- ◆ **Coherent oscillation instability is not a problem with the DRFB and ZMD so far.**

# High Power RF

Klystron
Toshiba (Canon)
E3786, E3732,
Power max : 1.2 MW (CW),
Gain : 55-60 dB,
Efficiency : ~65%

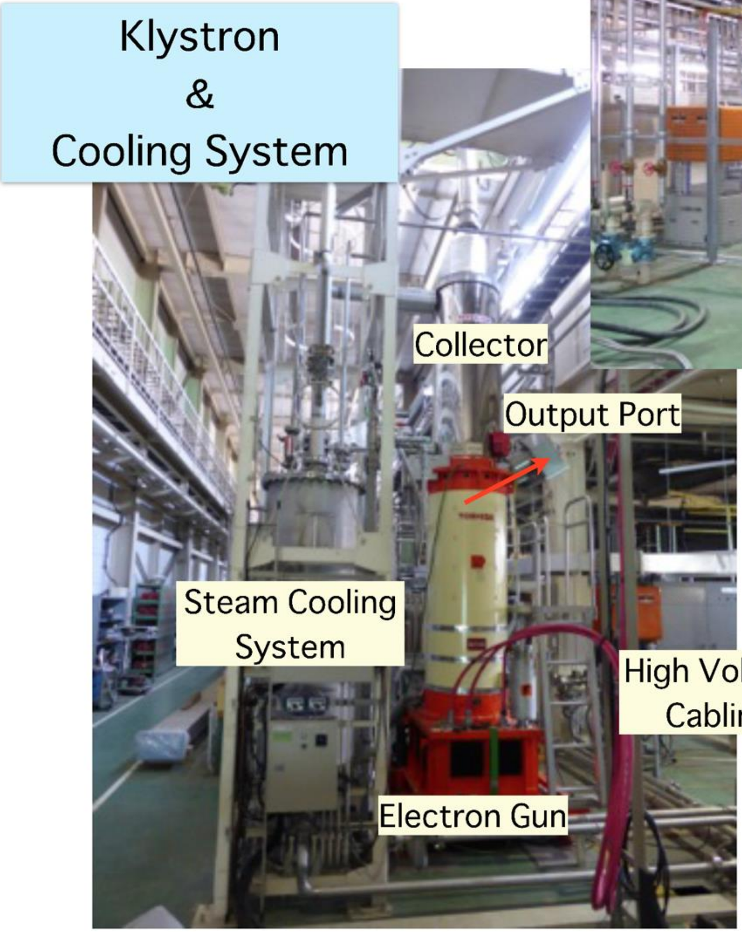
T.Okada



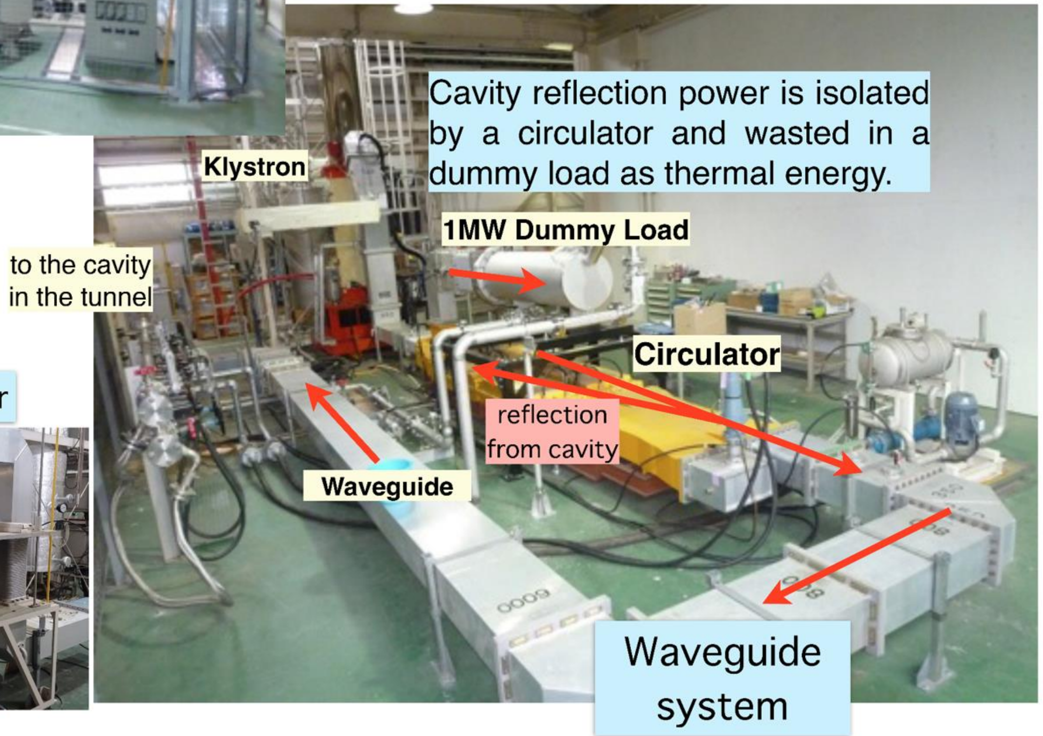




- Update klystron and power supply required for SuperKEKB for High Beam Current
- Expected lifetime of klystron is around 200,000 hour
- Preparing of spare is necessary for long term operation over 10 years

# High Power RF System （ex. of KEKB）

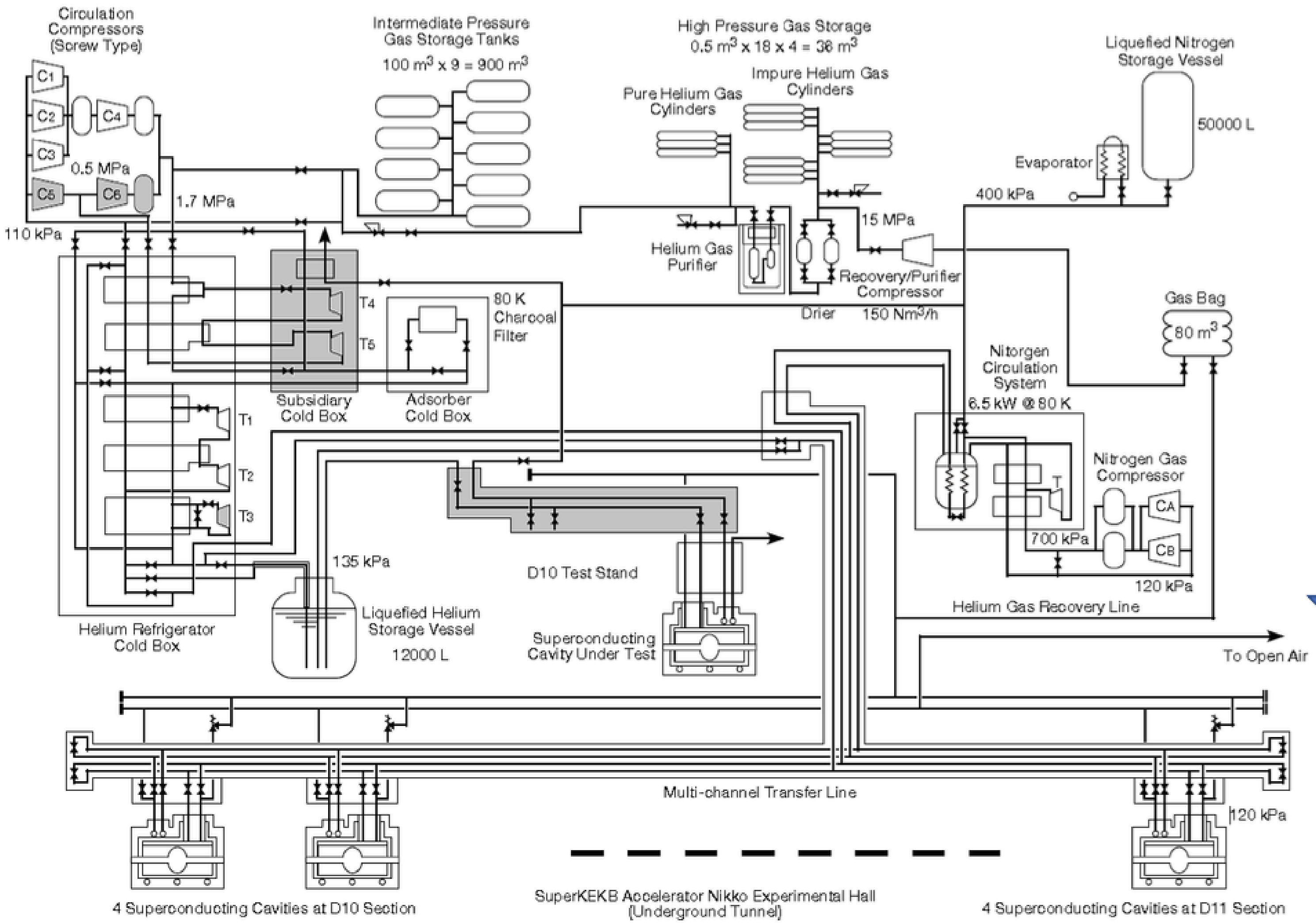





Introduction to Accelerators II 【RF- I】 December 2024

# Cryogenic system for Superconducting Cavities.

K.Nakanishi




1988
4kW @ 4.4K
(Design)

Compressor (C5,C6) were added.

Supercritical turbine expander (T3) was added.

1989
6.5kW @ 4.4K
(Design)
8.1kW @ 4.4K
(Achieved)

# KEKB (1998~2010) SuperKEKB (2016~)

K.Nakanishi

| Components | | Heat loads |
|---|---|---|
| Cryostat | 30 W/cryostat x 8 | 240 W |
| Transfer Lines (380m) | | 412.4 W |
| Cold Valves & Joints | | 147 W |
| RF Loss | 100 W/cavity x 8 | 800 W |
| **Total** | | **~1600 W** |

Compensation heater power is included

- The heat load was smaller than TRISTAN's.
- The RF loss is stable during beam operation.
- The compensation heaters are even used.
- The refrigerator is powerful enough.