The 20th KEKB Accelerator Review Committee (2015.02.23)

Status of RF System

T. Kobayashi from SKB RF Team

Outline

1. Introduction

2. Normal Conducting Cavity

    - ARES Cavity

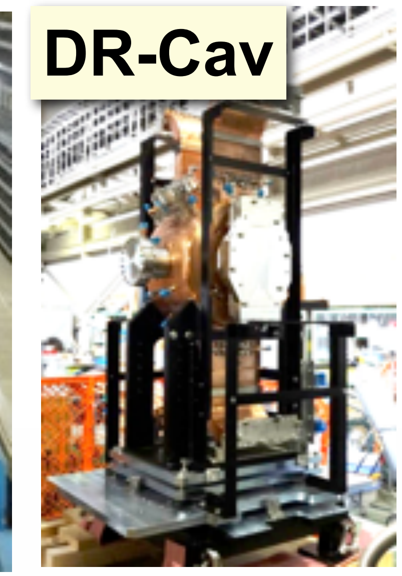
    - DR Cavity

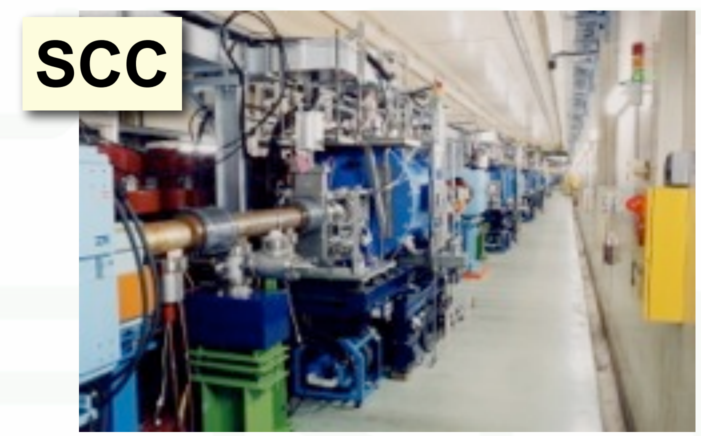
3. Super-Conducting Cavity

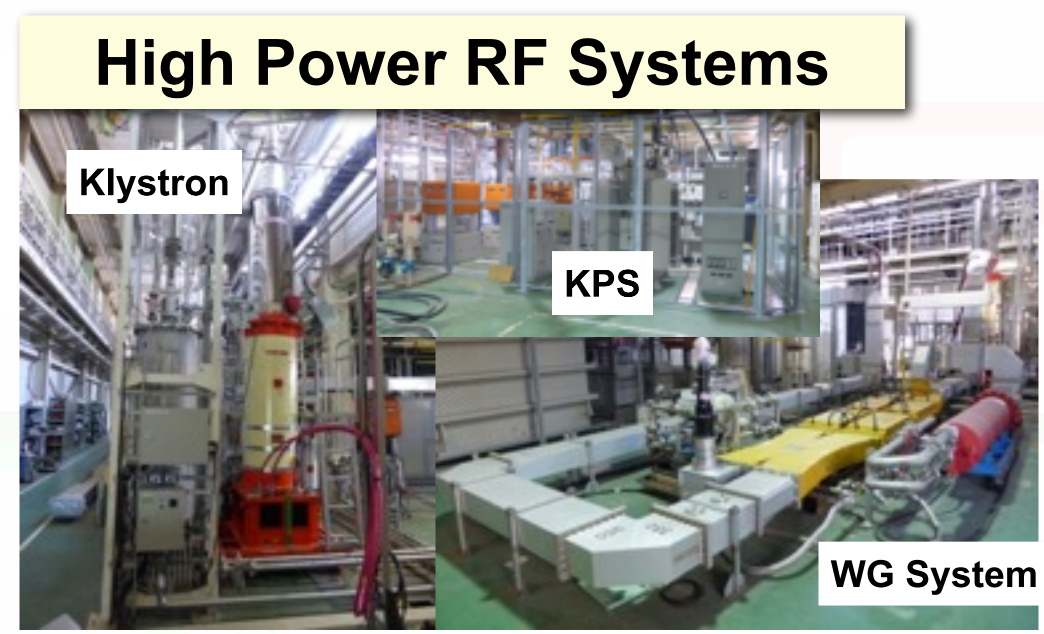
4. High Power RF System (Kly, KPS, WG)

5. Low Level RF Control System

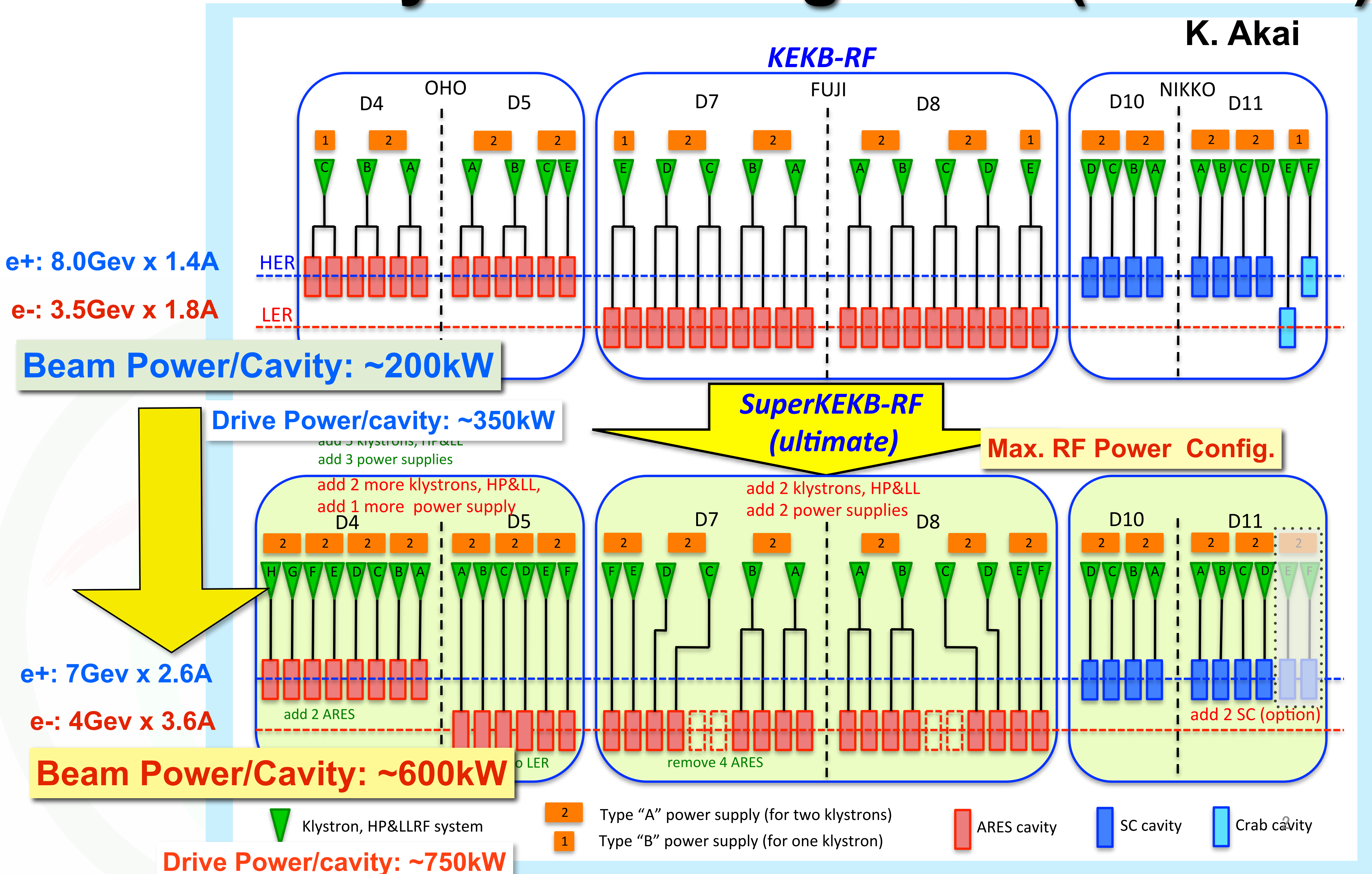
6. Summary







Intro.: RF System Arrangement (ultimate)

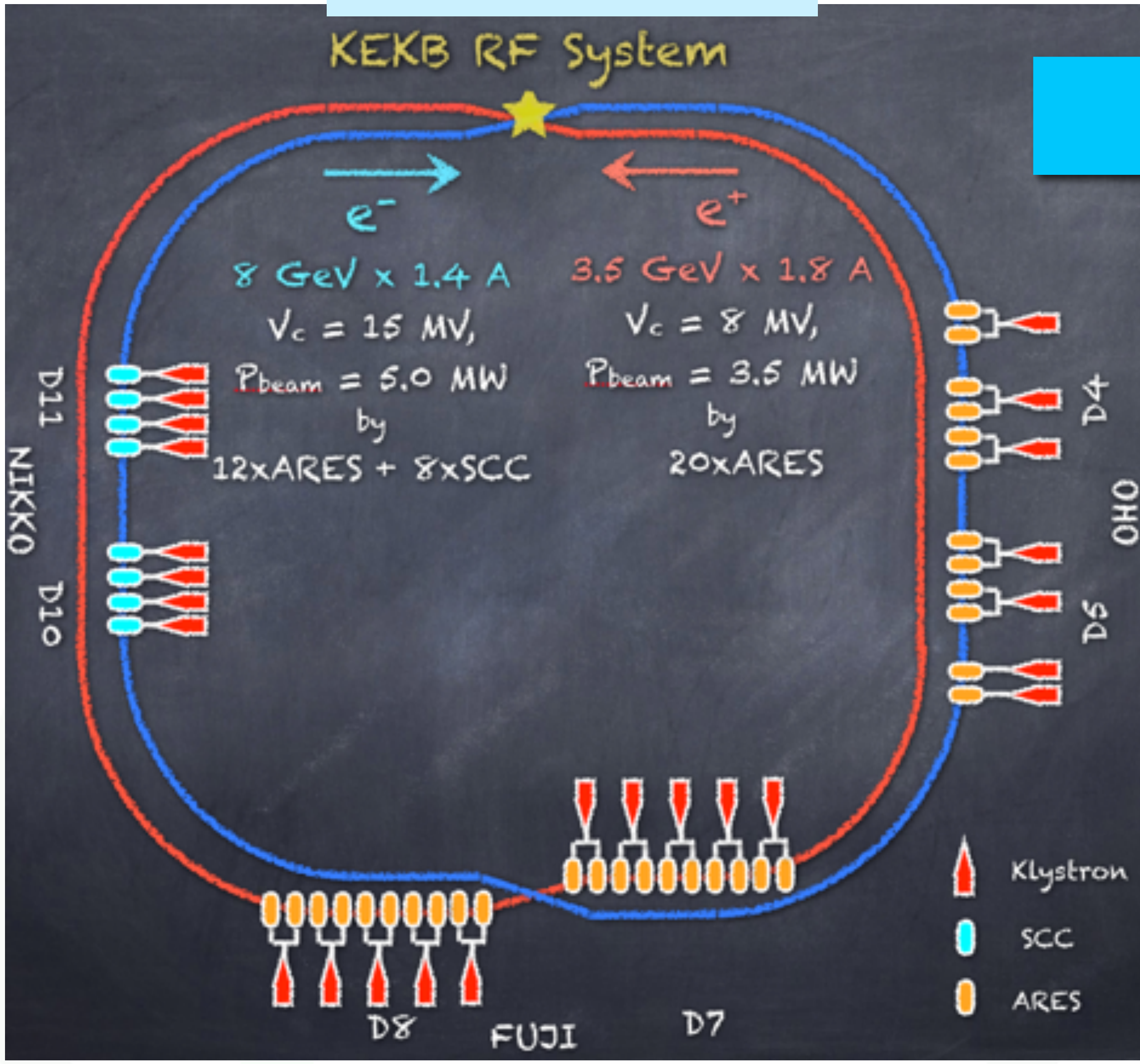


➡ **One-to-one configuration** for every ARES (One klystron drives one cavity).
➡ **Upgrade** of **input coupler** for the ARES (up to β~6, 800-kW input power capable)
➡ **Addition** of **new HOM Damper** for the SCC as a measure against beam-induced HOM-power rising.

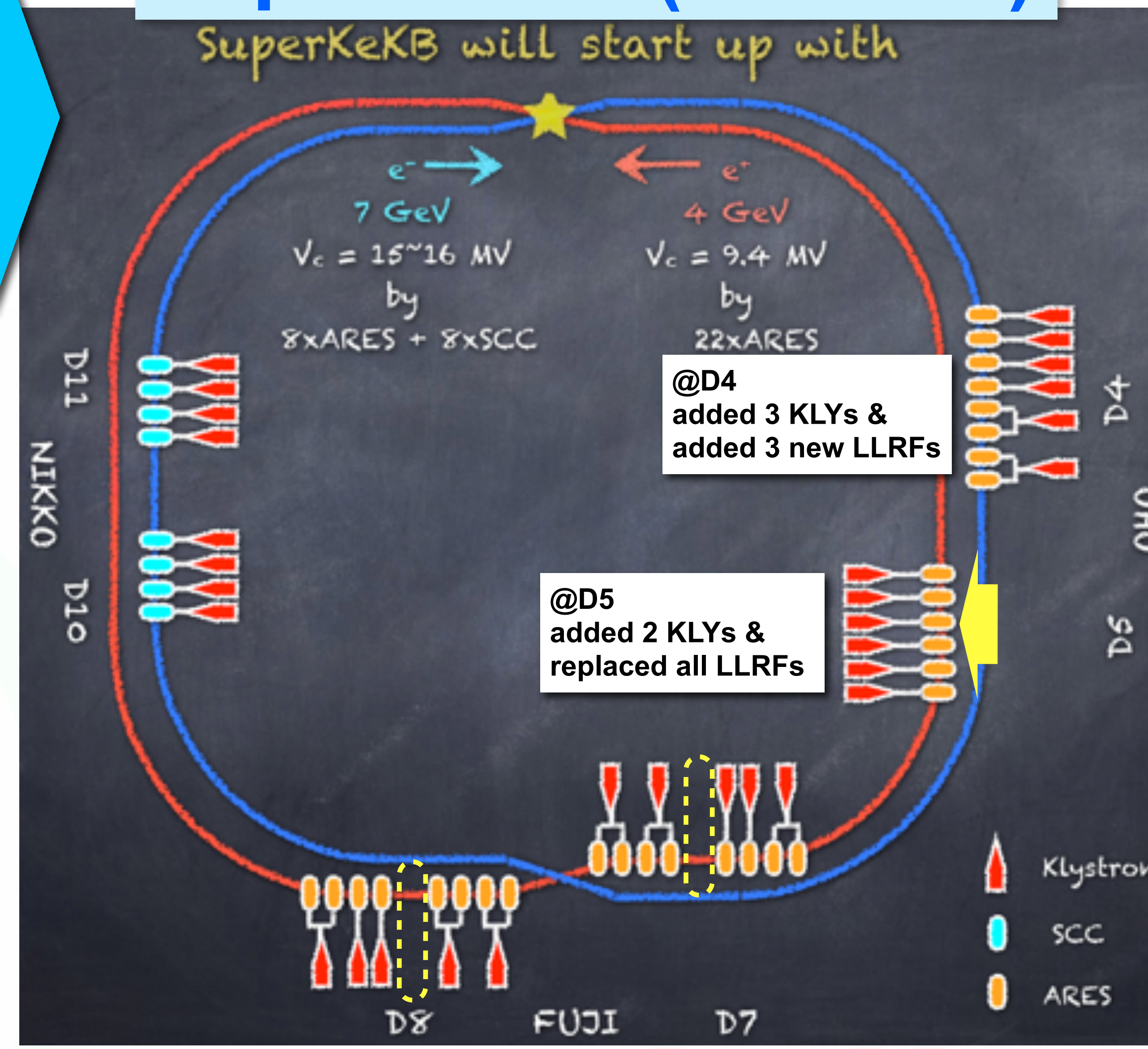
- add 9 klystrons and 3 PS's more.
- increase and reinforce WG systems.

Relocation of ARES Cavity for Phase-I

KEKB



SuperKEKB (Phase 1)



Relocation of ARES cavities almost completed.

- Oho D4: Two cavities added.
- Oho D5: Six cavities moved from HER to LER. → 1:1 config.
- Fuji D7: Two cavities removed.
- Fuji D8: Two cavities removed.

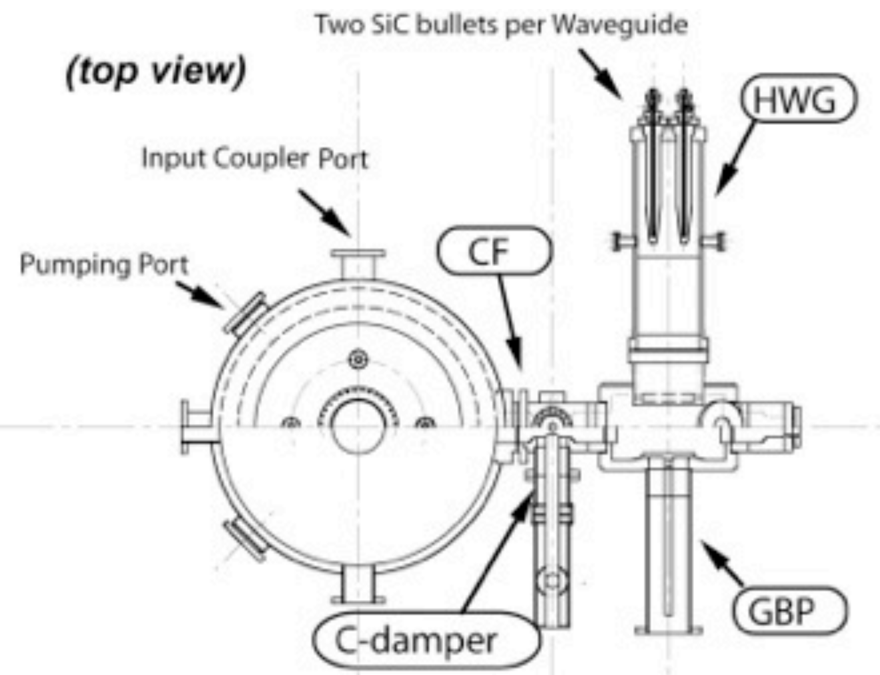
ARES Cavity

ARES Cavity

Accelerator Resonantly-coupled with Energy Storage

3-cavity system stabilized with the π/2-mode operation

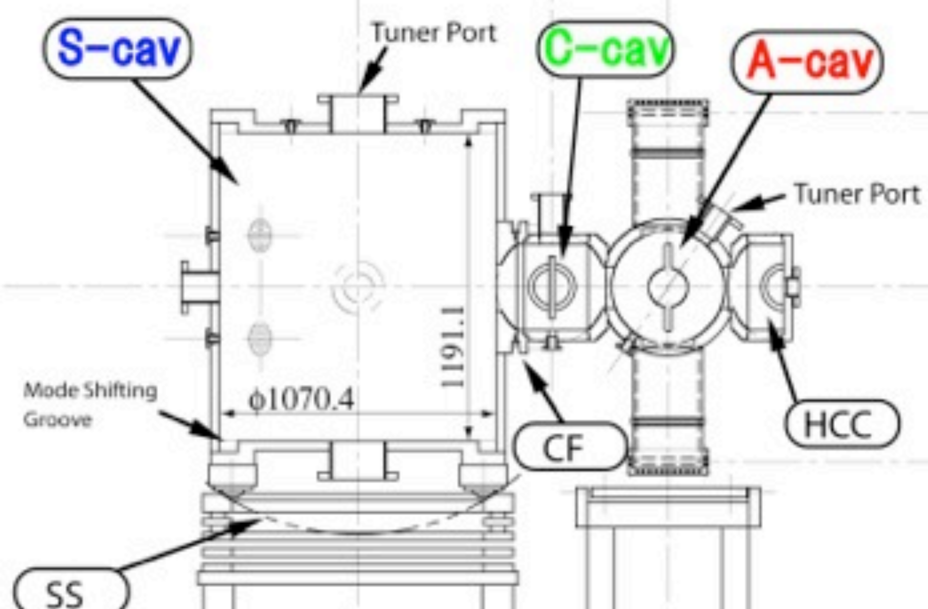
T. Abe (2014.03)



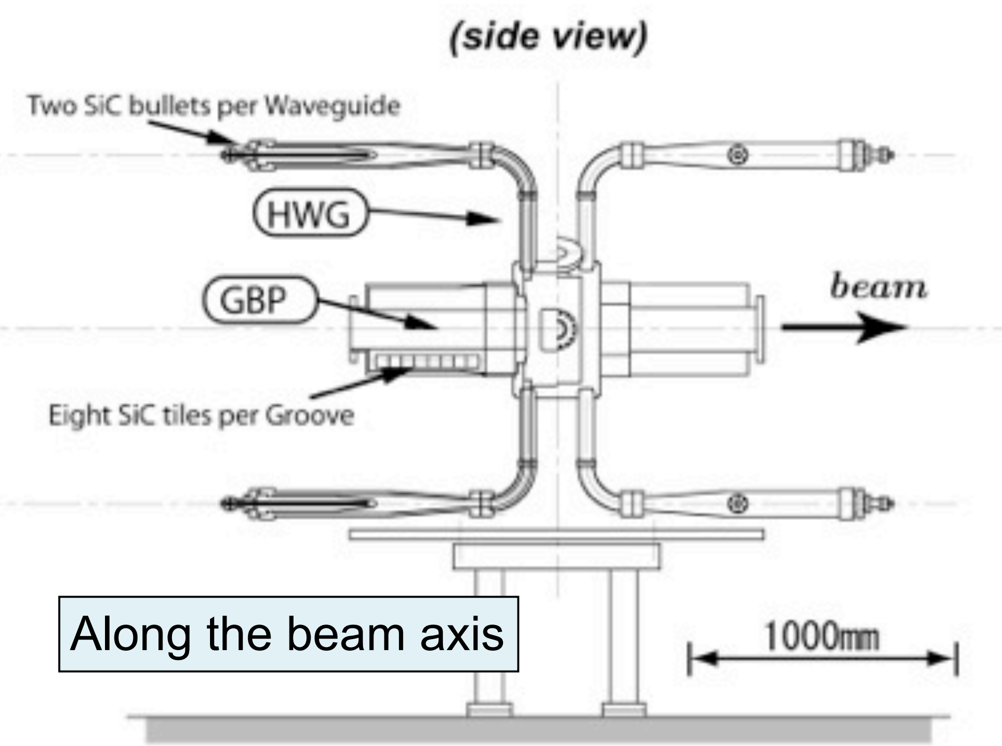
consists of

- HOM-damped accelerating cavity (**A-cav**),
- Energy-storage cavity with TE013 (**S-cav**),
- Coupling cavity (**C-cav**) with a parasitic-mode damper.

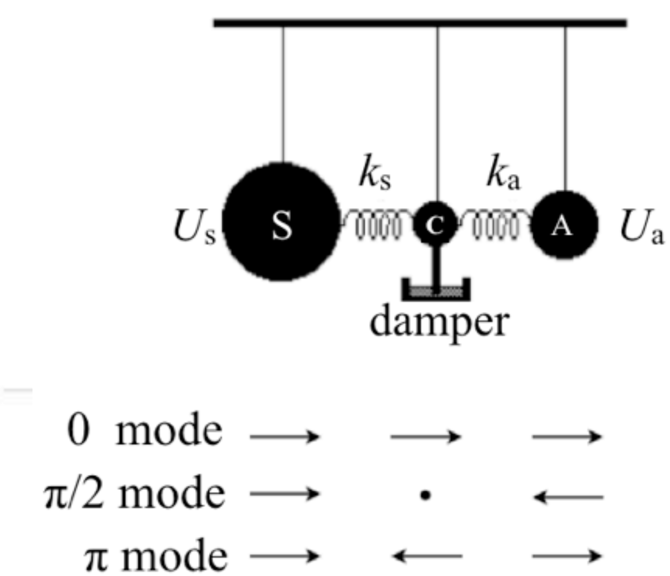
f_{RF}	508MHz	
U_s / U_a	9	
R/Q_0	15Ω	for the π/2 accelerating mode
Q_0	1.1 x 105	
V_c	0.5 MV	
P_c	150 kW	60 kW (acc. cav.) + 90 kW (str. cav.)



Perpendicular to the beam axis



Along the beam axis



$U_s/U_a = k_a^2/k_s^2$ for π/2 mode

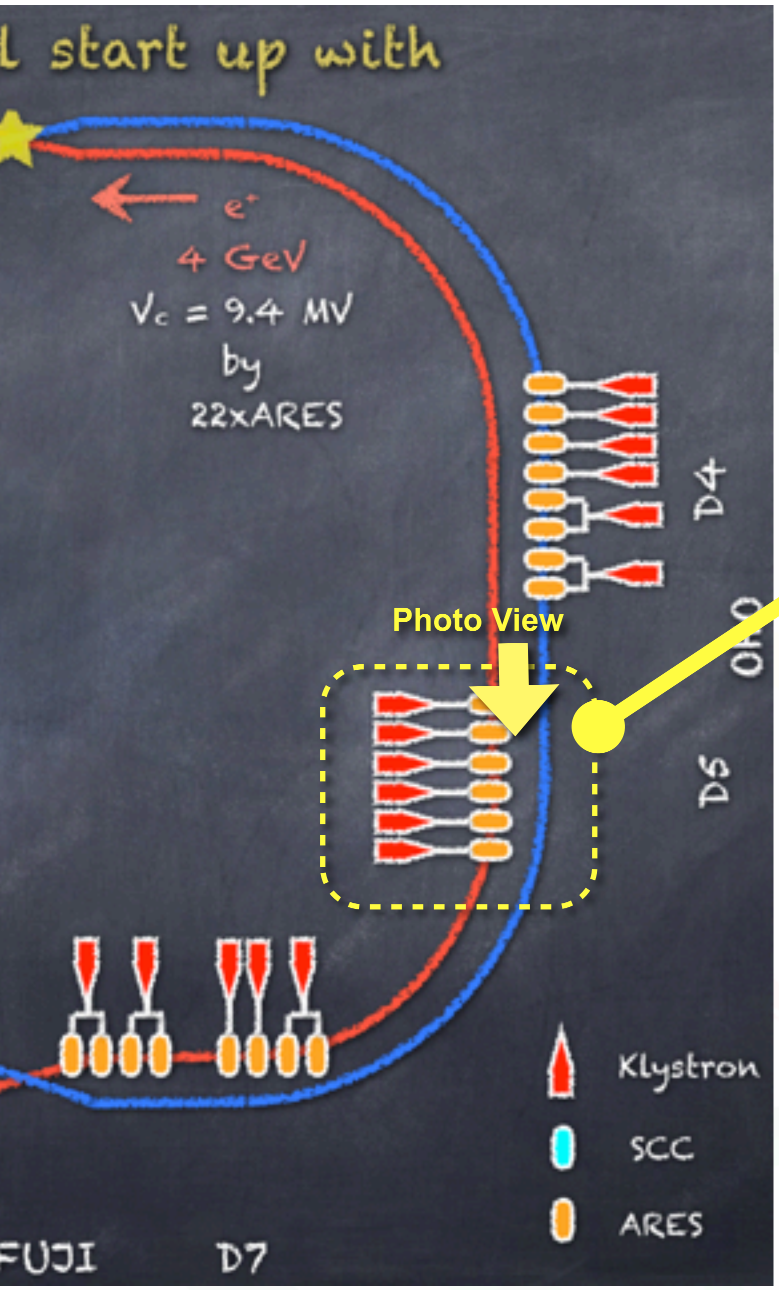
$\Delta f_{\pi/2} = \Delta f_a / (1 + U_s/U_a)$

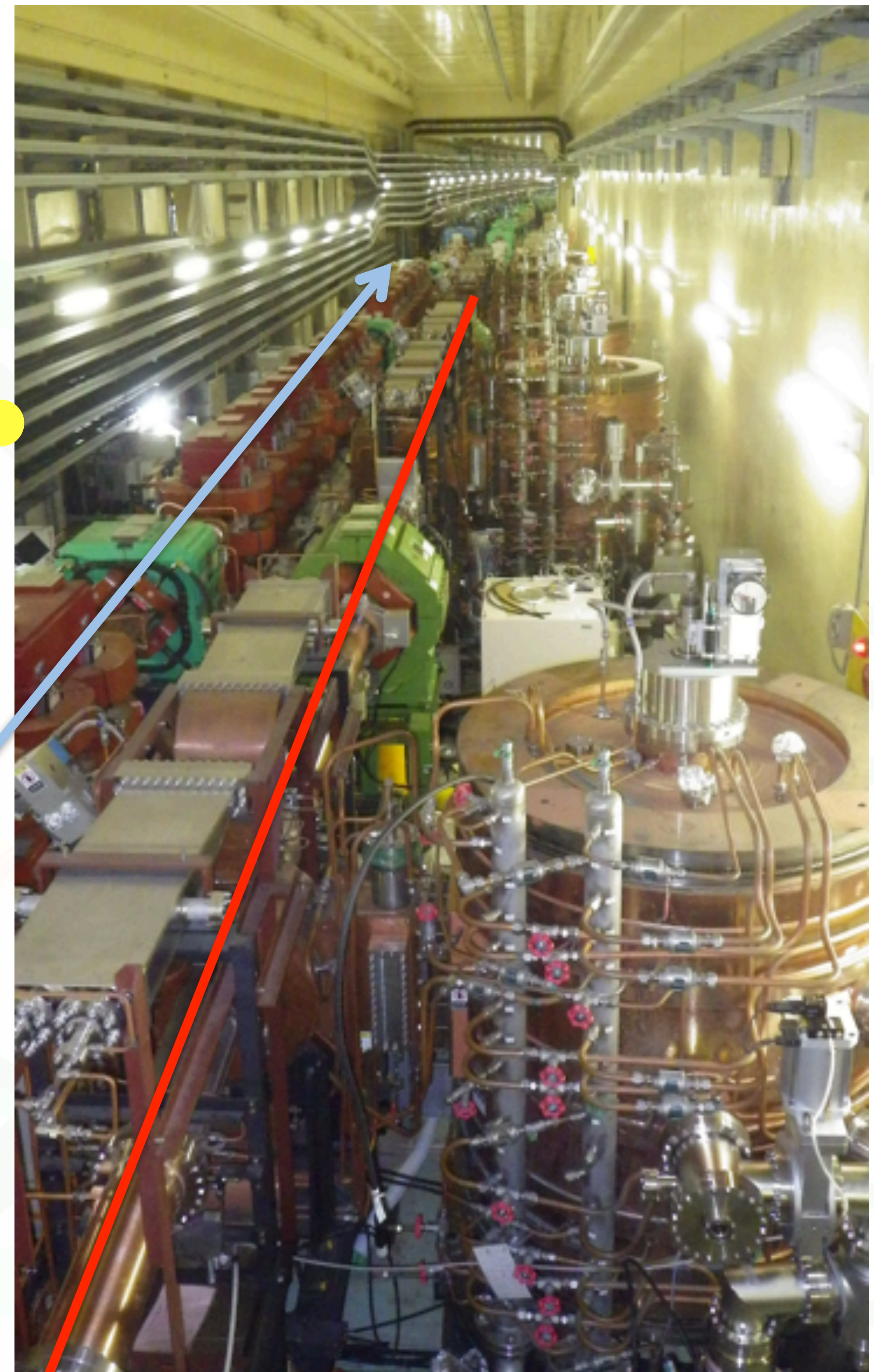
Successful Operation of the 32 ARES Cavities at KEKB

<Topic>
ARES

Relocation of ARES Cavity @Oho D5

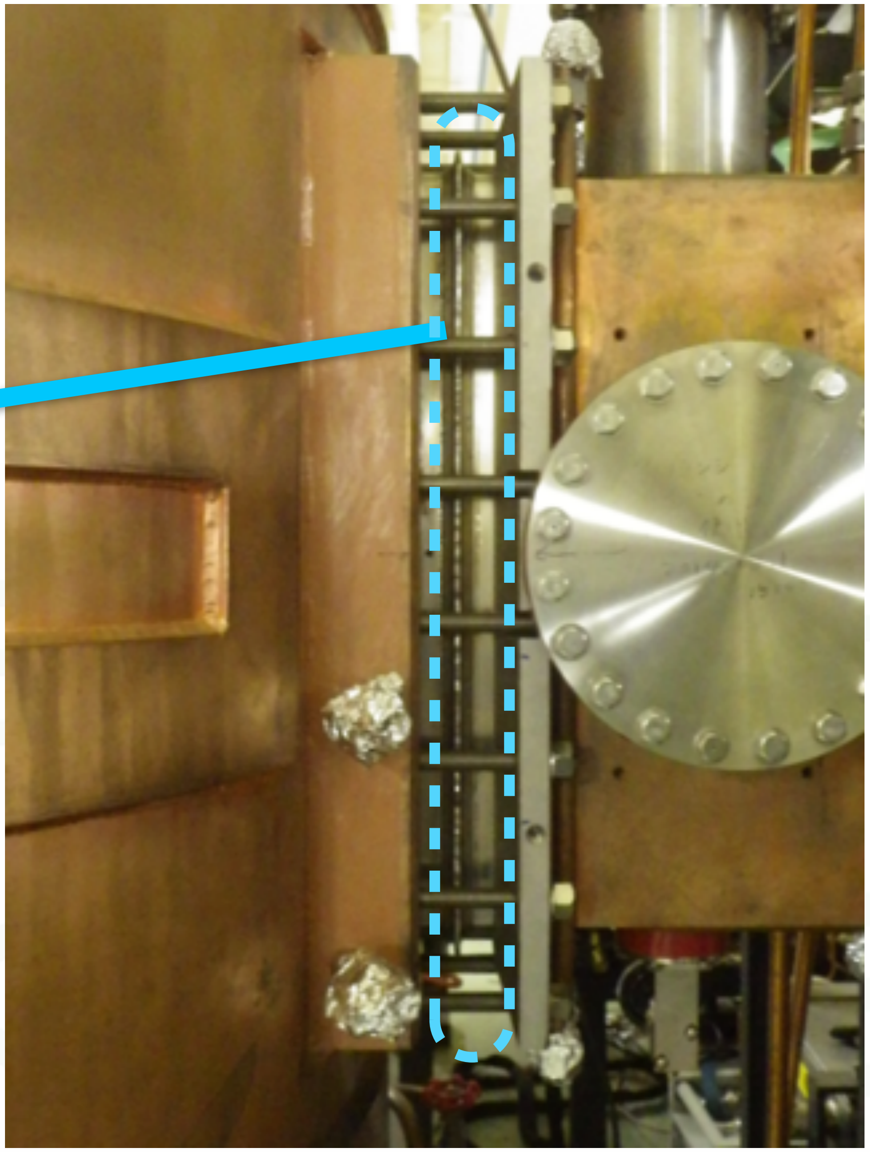
ARES cavities along the LER beam line in Oho D5.





All of 6 cavities were moved from HER to LER.

Relocation of ARES Cavity

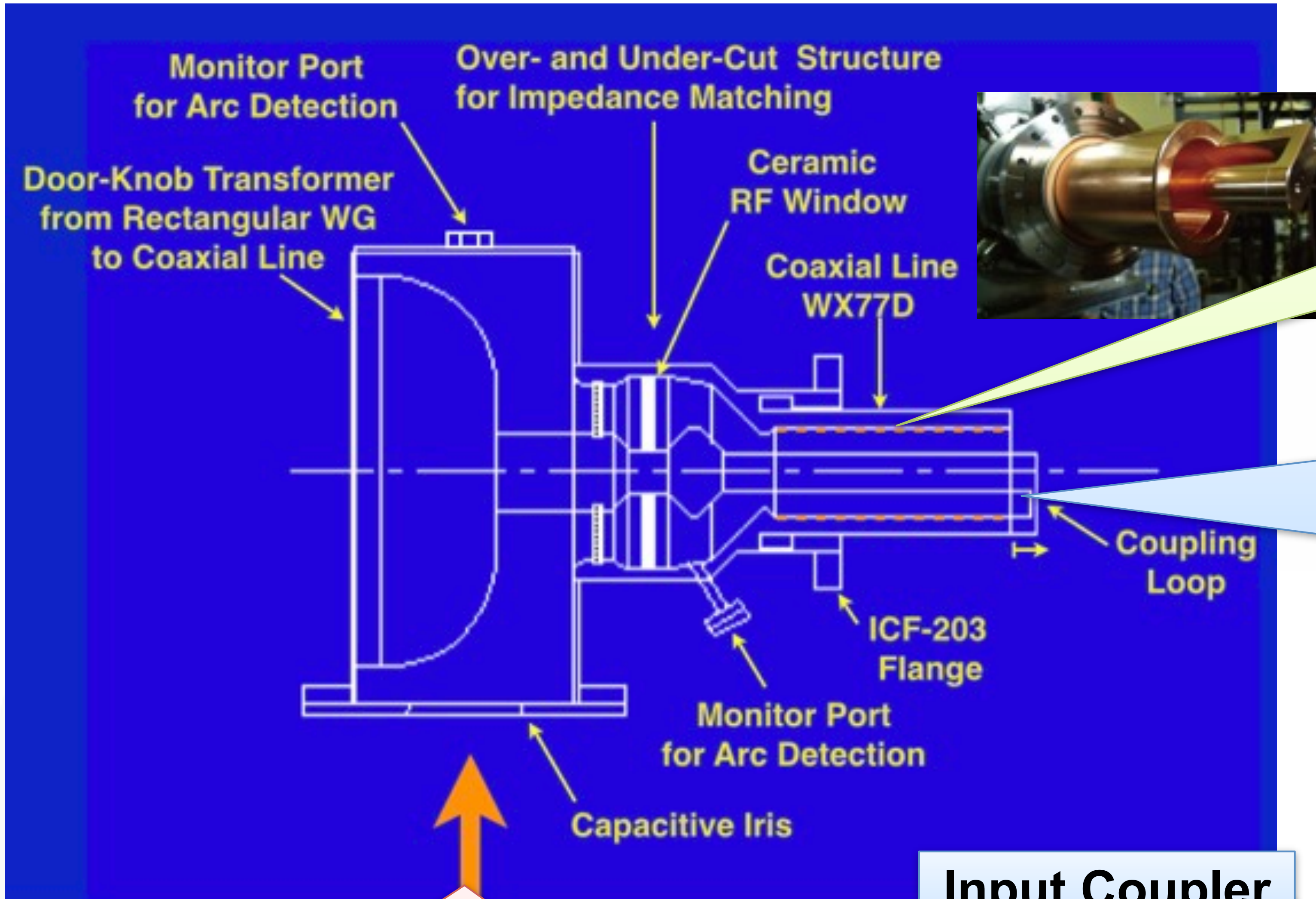


A-cav (+ C-cav) and S-cav are moved separately, then connected with each other after the installation.

Lip welding for vacuum seal at the flange connection between the coupling and storage cavities was processed after the accelerating cavity aligned along the LER beam line.

<Topic>
ARES

Performance Upgrade of Input Coupler



Input Coupler

Fine grooving inside the outer conductor of the coaxial line in order to suppress multipactoring discharge for high power hadndling.

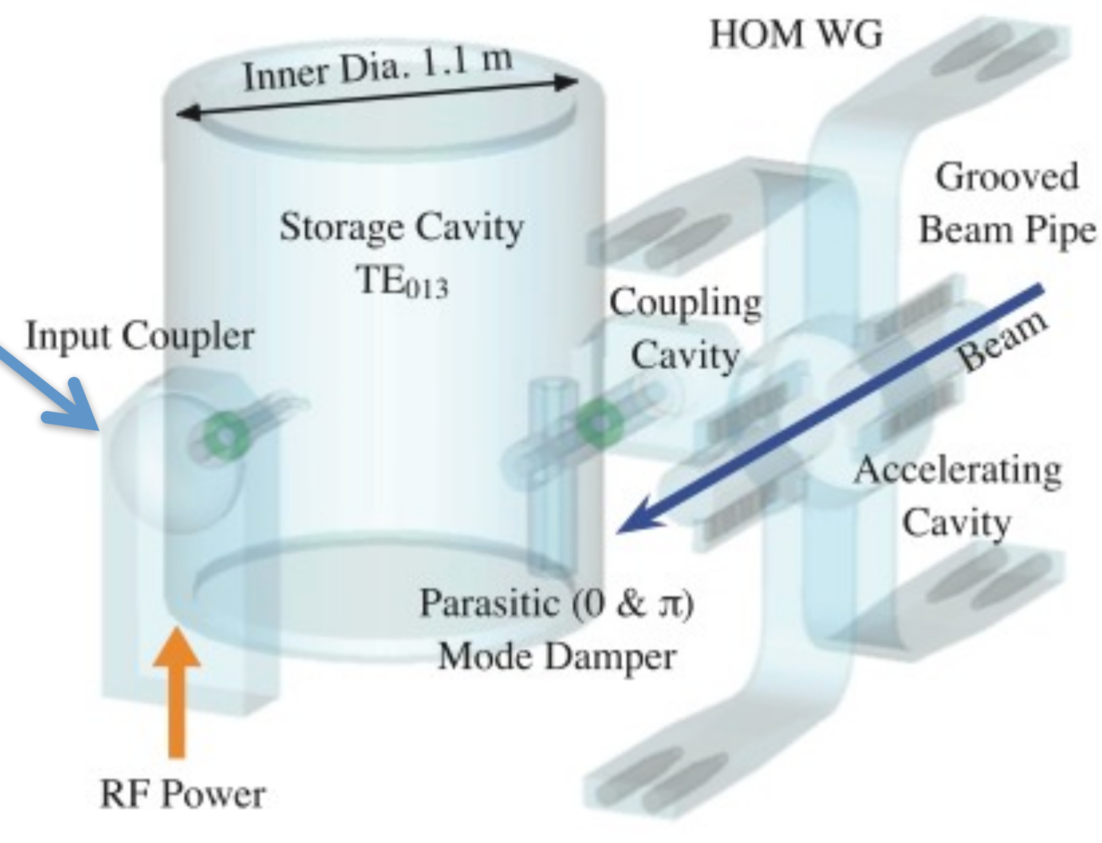
The coupling loop was extended to increase the input coupling factor β. (up to β = 6)

The optimum coupling factor β_{opt} is given by $\beta_{opt} = 1 + P_{beam}/P_c$.

Power Handling Capability (Spec.)

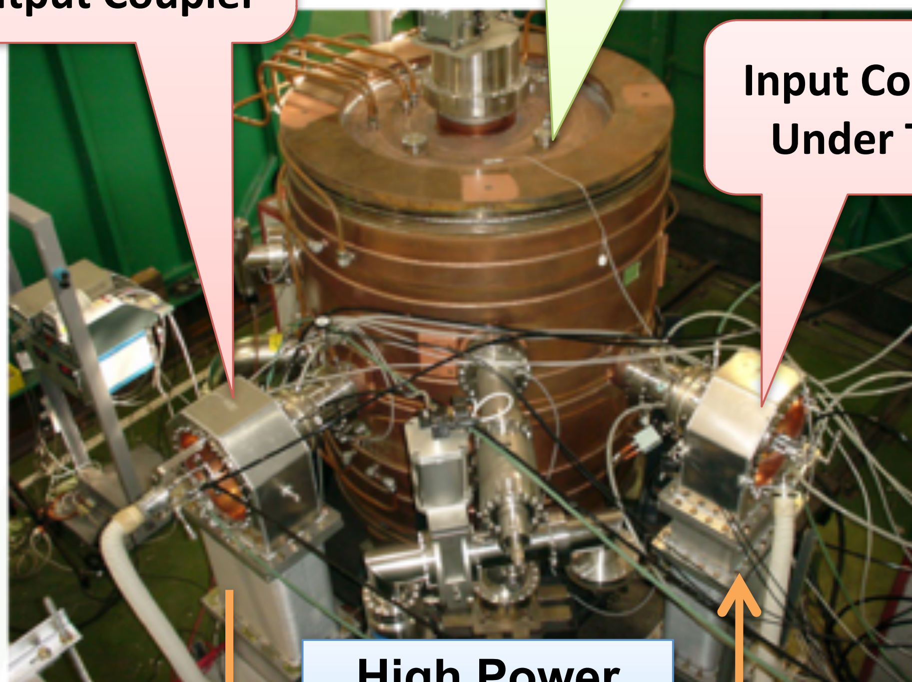
	P_{input}		P_c		P_{beam}	
SuperKEKB	: 750 kW	=	150 kW	+	600 kW	(β_{opt} = 5)
KEKB	: 350 kW	=	150 kW	+	200 kW	

P_c = 150 kW generating V_c = 0.5 MV per ARES cavity.

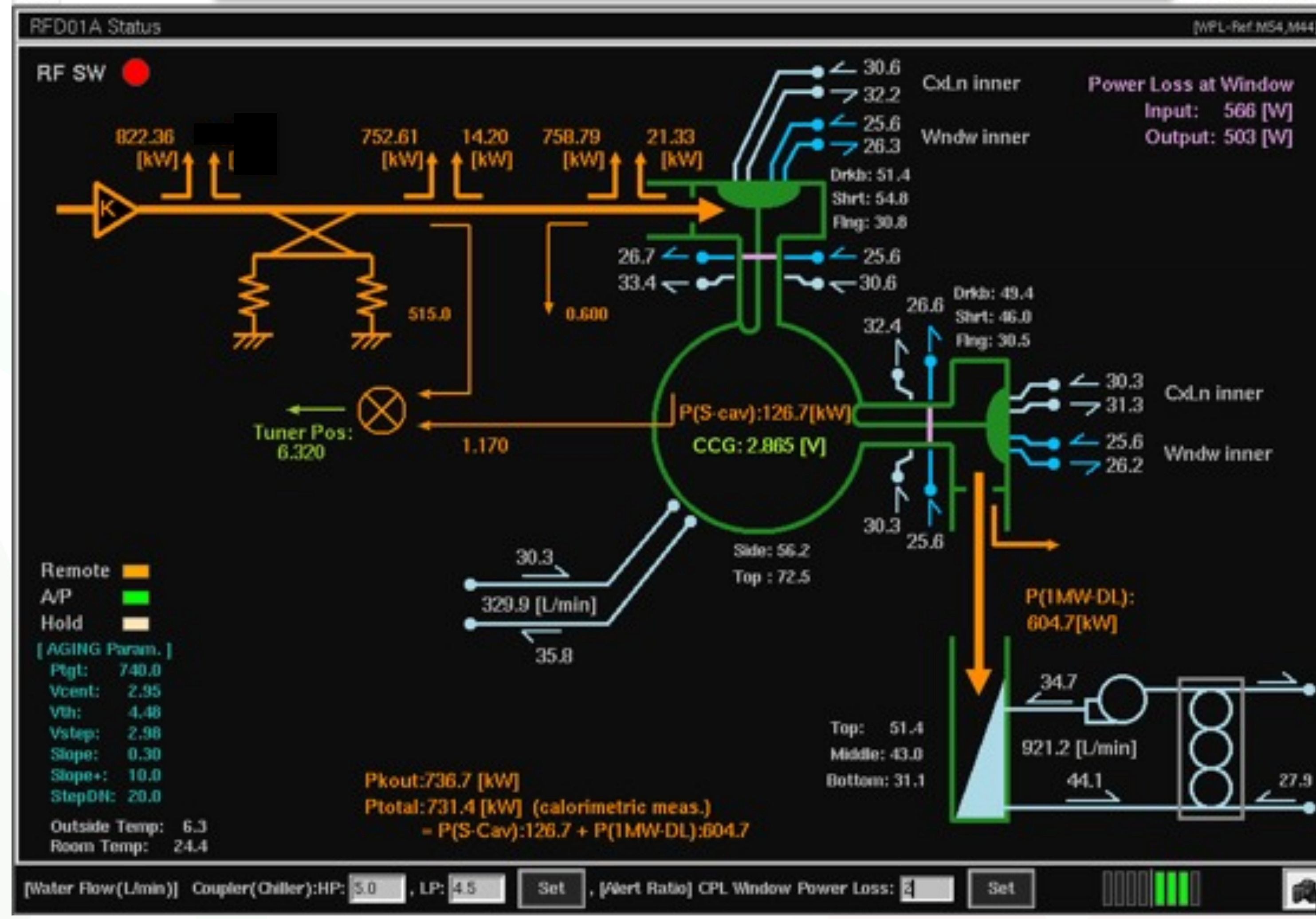


3D Transparent View of ARES Cavity System

Production & Processing of Upgraded Input Couplers



Snapshot of Status Monitor for RF Processing



Status & Plans

D4+D5 = 10 ARES's (1:1)

- So far, 13 input couplers have been processed up to 750-800 kW.
- Every ARES cavity in Oho D5 has been equipped with an upgraded coupler.
- Additionally in Oho D4, upgraded couplers will be installed in the RF stations each configured as one klystron driving one ARES cavity before T=0.

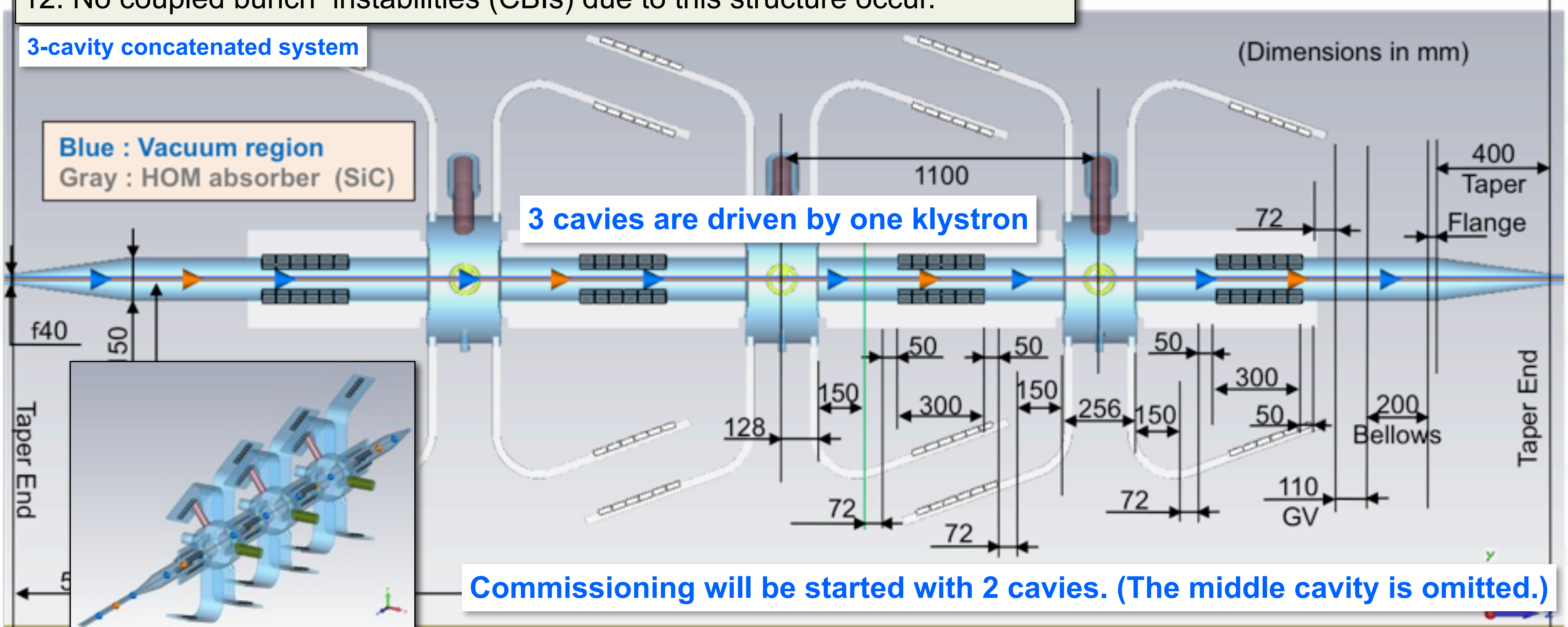
Damping Ring Cavity

Acc. Structure for the DR

T. Abe (2014.03)

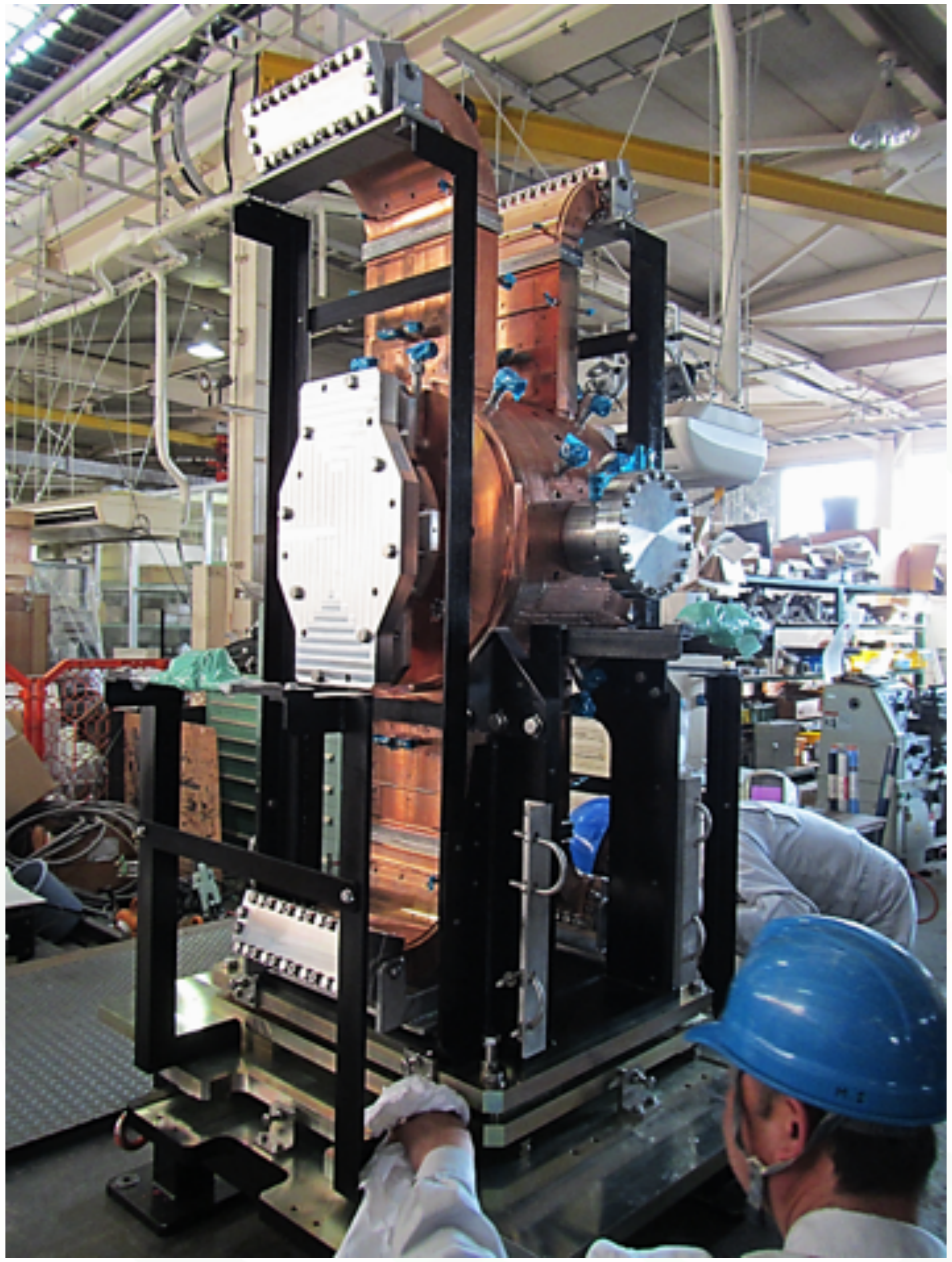
Based on the ARES cavity with the long successful operation at KEKB

1. Accelerating-Mode Frequency: 508.887[MHz] (same as for the MRs)
2. ~~Cavity Voltage (spec.): 0.7[MV/cav] (→Wall-loss power: ~120kW/cav)~~
3. Cavity Voltage (spec): 0.8[MV/cav] (→Wall-loss power: ~150kW/cav) → We can supply total V_c : 2.4MV at maximum.
4. Max. stored beam current: 70.8[mA] → Very low loading compared to the (Super)KEKB-MRs
5. HOM absorbers: Silicon Carbide (SiC) tiles → More compact than the SiC bullets
6. Grooved Beam Pipe (GBP) common between cavities
7. Cavity-GBP Joint with a weld-ring gasket (not using a usual flange)
8. *"Multi Single Cell"* structure
9. Reuse of high-power input couplers and tuners proven at KEKB-MRs/ARES
10. Good vacuum in cav. (~10^{-6}[Pa]) needed for high-power input couplers. → Pumping port on each cavity
11. Loss factor (incl. the taper sections): 2.4 [V/pC] (for σ_z=6.0mm)
12. No coupled bunch instabilities (CBIs) due to this structure occur.



DR Cavity No. 2

High power test result of the Cavity No. 1 was reported last ARC.



Just after the delivery to KEK

The Cavity No. 2

- **Fabricated in JFY2013 with the same structure, method, and procedure as Cavity #1.**

  Inner surface of both end plates are electropolished in the same way as the #1.

- **High-power tested from May 12 to July 4 in 2014**

Table 1: Design parameters of the DR cavity

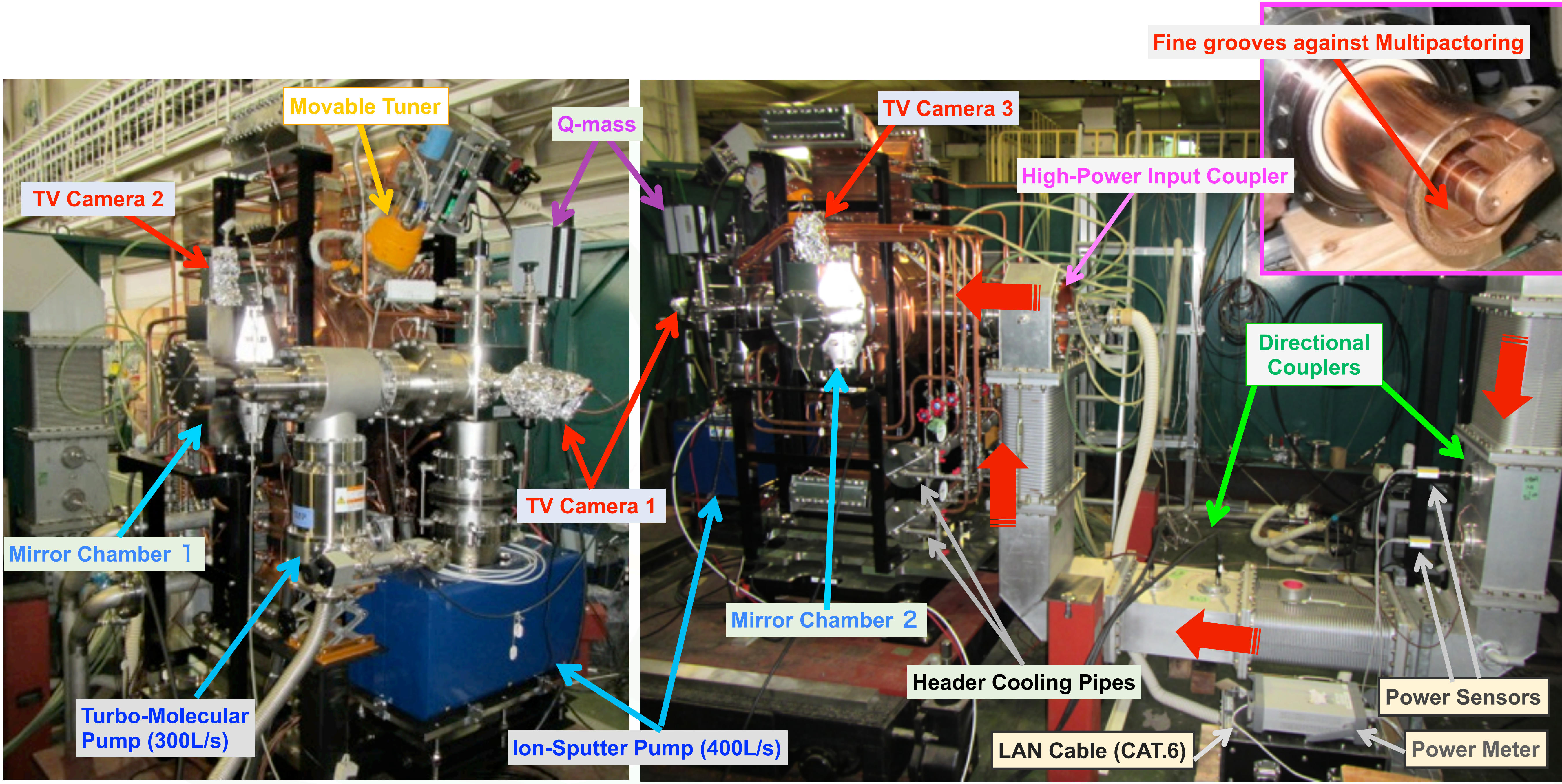
Frequency	508.887	MHz	
R_{sh}/Q_0	150	Ω	
Q_0	≈ 30000		
Cavity Voltage	0.8	MV	/cavity
Wall-Loss Power	≈ 140	kW	/cavity

In DR operation: 0.70 MV/cavity

<Topic>
DR-Cav

Setup of High Power Test for the Cavity No. 2

@D1-A test stand



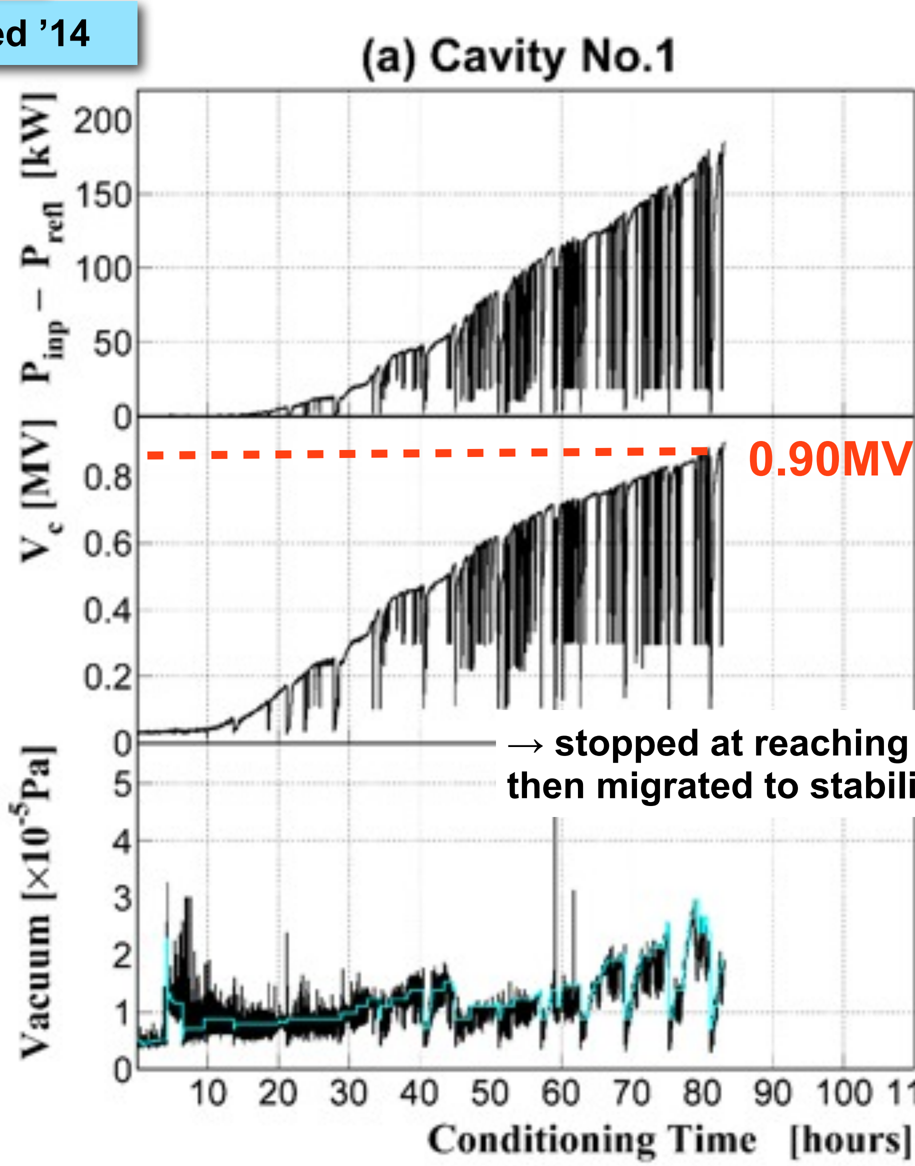
<Topic>
DR-Cav

Conditioning Histories

No.1

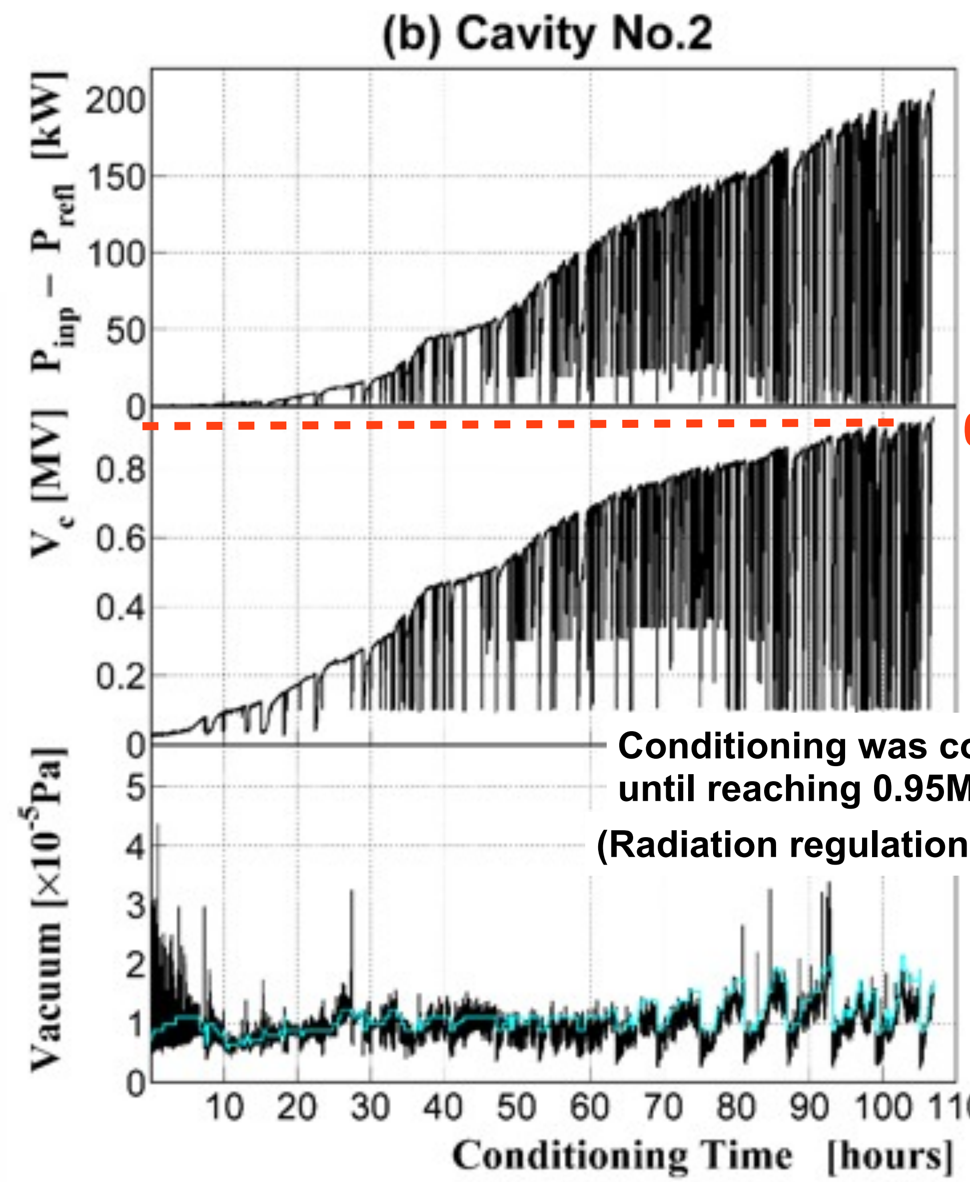
✓83 hours to reach 0.90MV/cavity

Reported '14



No.2

✓ 95 hours to reach 0.90MV/cavity
✓107 hours to reach 0.95MV/cavity



Auto conditioning sequencer was applied for the process.

The light blue lines indicate the reference vacuum pressure specified by the computer controlled automatic aging. If the vacuum pressure is higher than the reference, P_{in} is slightly stepped down until the vacuum pressure becomes lower than the reference, and then P_{in} is slightly stepped up as long as the vacuum pressure is lower than the reference.

✓P_{in} (P_{refl}) : *input power to (reflected power from) the cavity*

✓*Wall-loss power:* $P_{wall} = P_{in} - P_{refl} = \sim 0.99 \times P_{in}$

✓***Cavity No.2 reached 0.95MV/cavity successfully.***

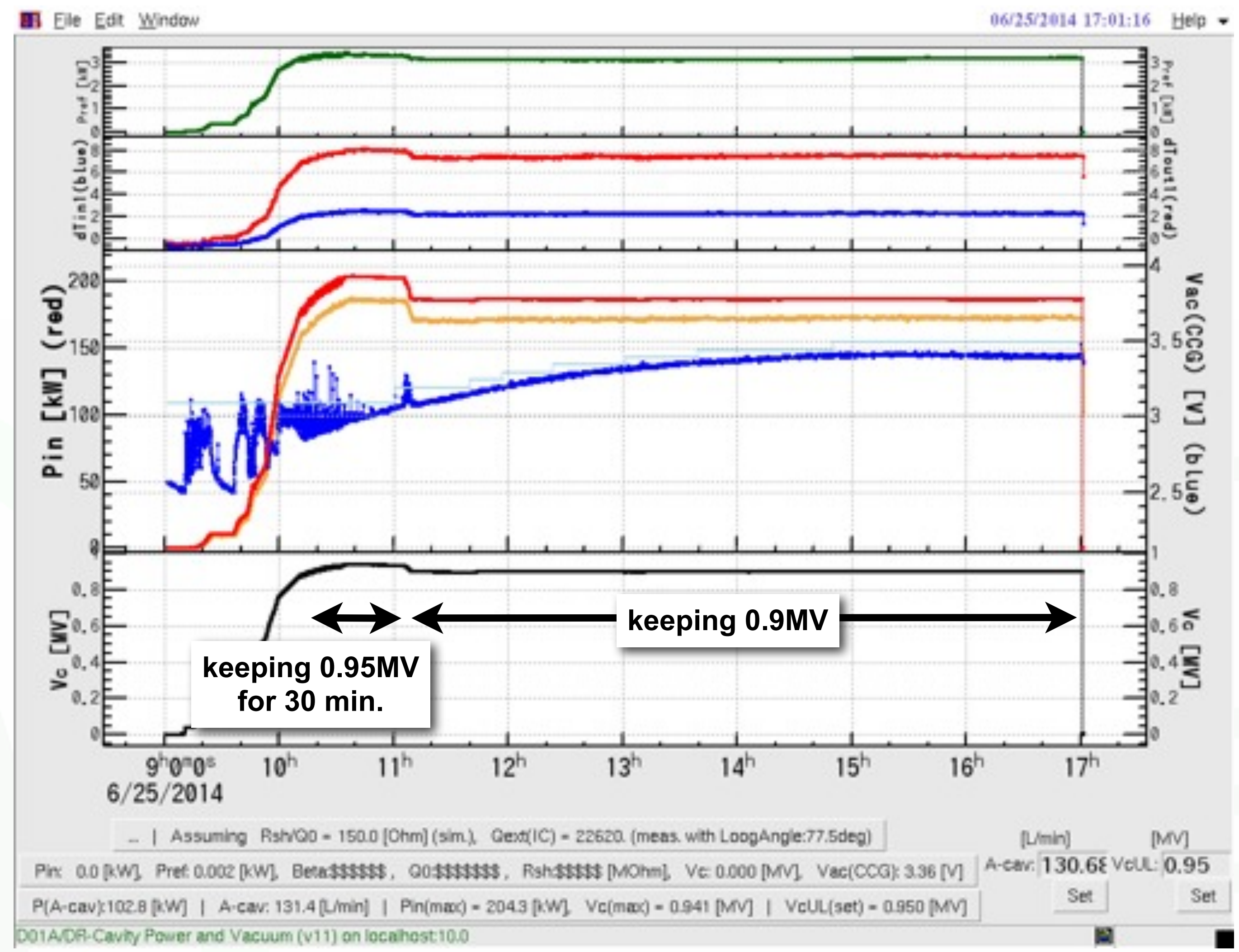
✓***Comparable conditioning speeds btwn Cavity No. 1 and 2***

Stability Evaluation with Keeping 0.90MV/cavity

After reaching 0.95MV, Stability was evaluated by keeping voltage at 0.9 MV

(In DR operation: 0.70 MV/cavity)

Example of the daily histories →



■Cavity No.1: 3 breakdowns for 14.5 hours in total = $5.0^{+4.8}_{-2.7}$ /24hrs

■Cavity No.2: 11 breakdowns for 80 hours in total = $3.3^{+1.3}_{-1.0}$ /24hrs

Same stability between Cavity No. 1 and 2 within the statistics

<Topic>
DR-Cav

Conclusion on Cavity No.2

- The RF performance is equivalent to that of Cavity #1:
  - Comparable conditioning speed
  - Same stability at 0.90 MV/cavity

(In DR operation: 0.70 MV/cavity)

↓

“Passed“

↓

Cavity #1 and #2 will be installed in the DR tunnel in 2016, and will supply a total V_c of 1.4MV to the DR.

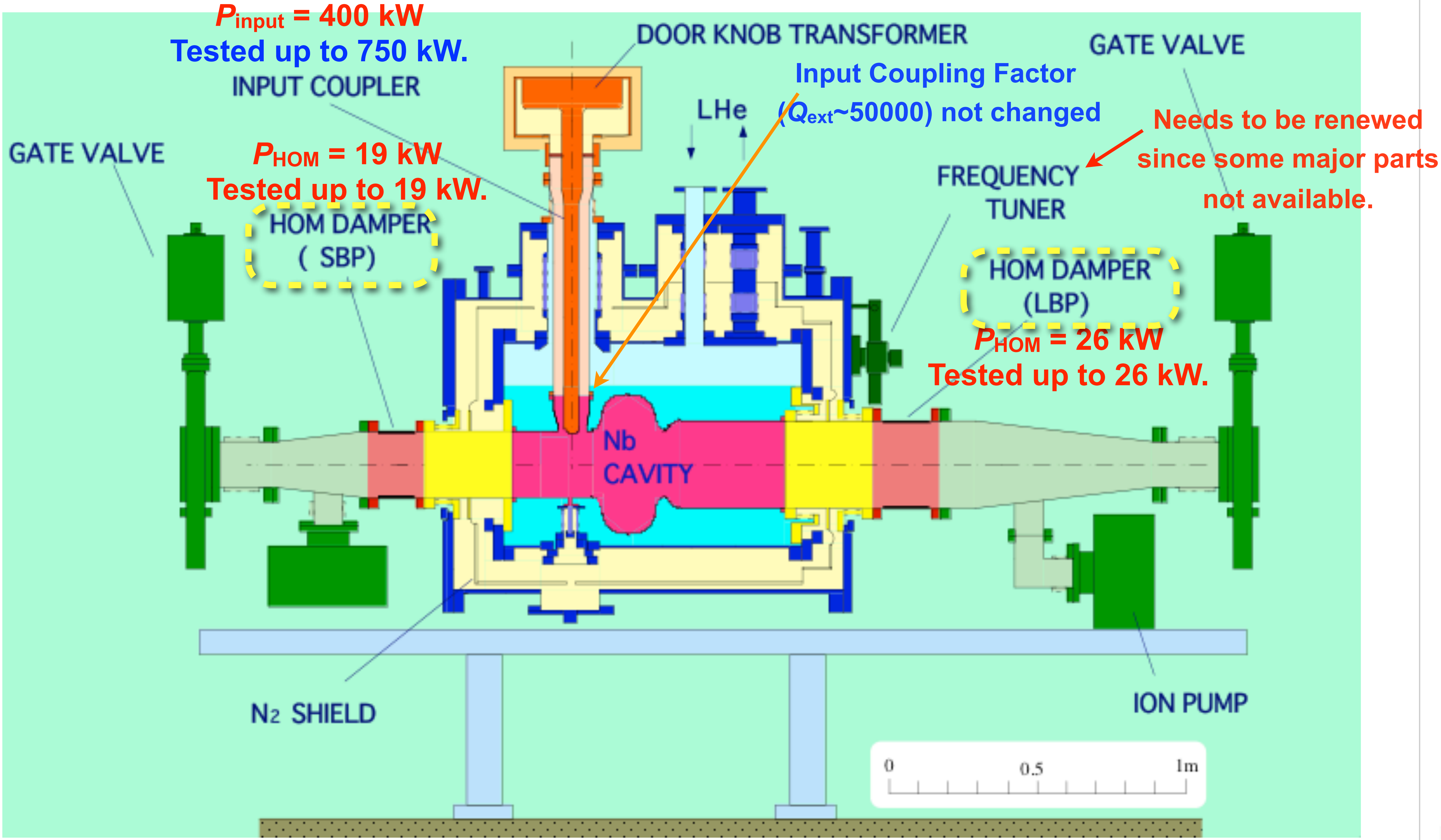
- **DR commissioning will start with 2 cavies.**
- **The fabrication of the No 3. relies on the budget.**
- **However, the need for the No.3 is not clear at present (It depends on the operation result).**

Super-Conducting Cavity

Superconducting Cavity

8 modules have been installed in Nikko for HER.

Y. Morita



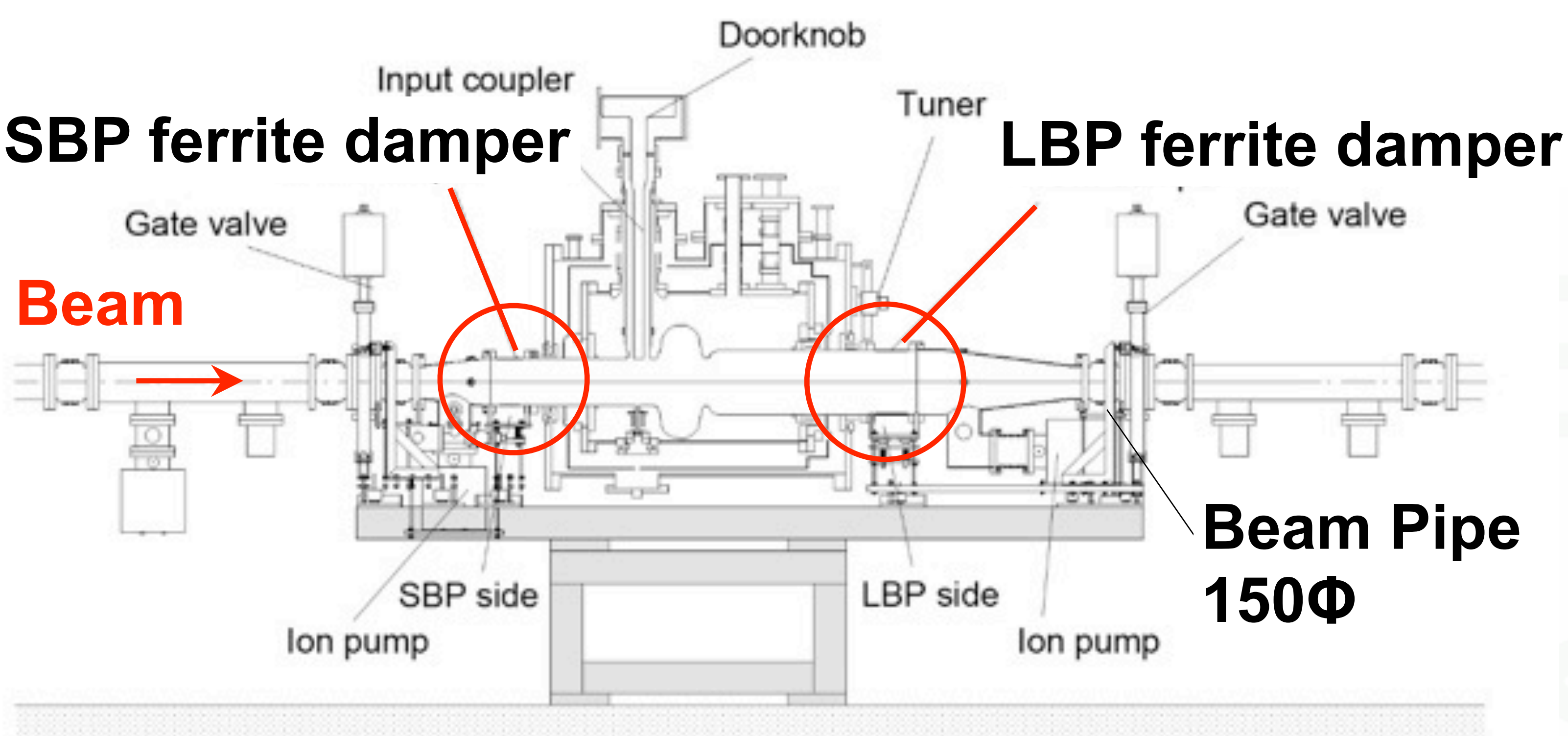
V_c = 1.5 MV, P_{beam} = 400 kW

/cavity

<Topic>
SCC

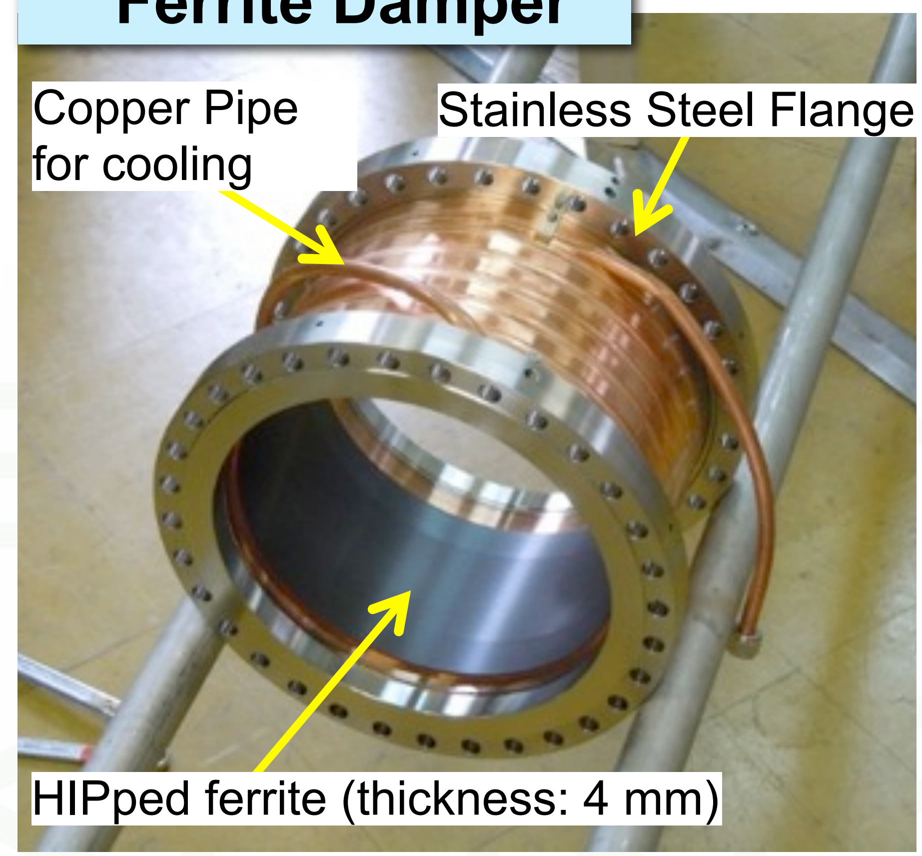
Large HOM Power
induced by high-charge and short-bunch beam

SCC module **Text**



(Presently-used)

Ferrite Damper



- **Expected large beam-induced HOM power in SuperKEKB/HER**

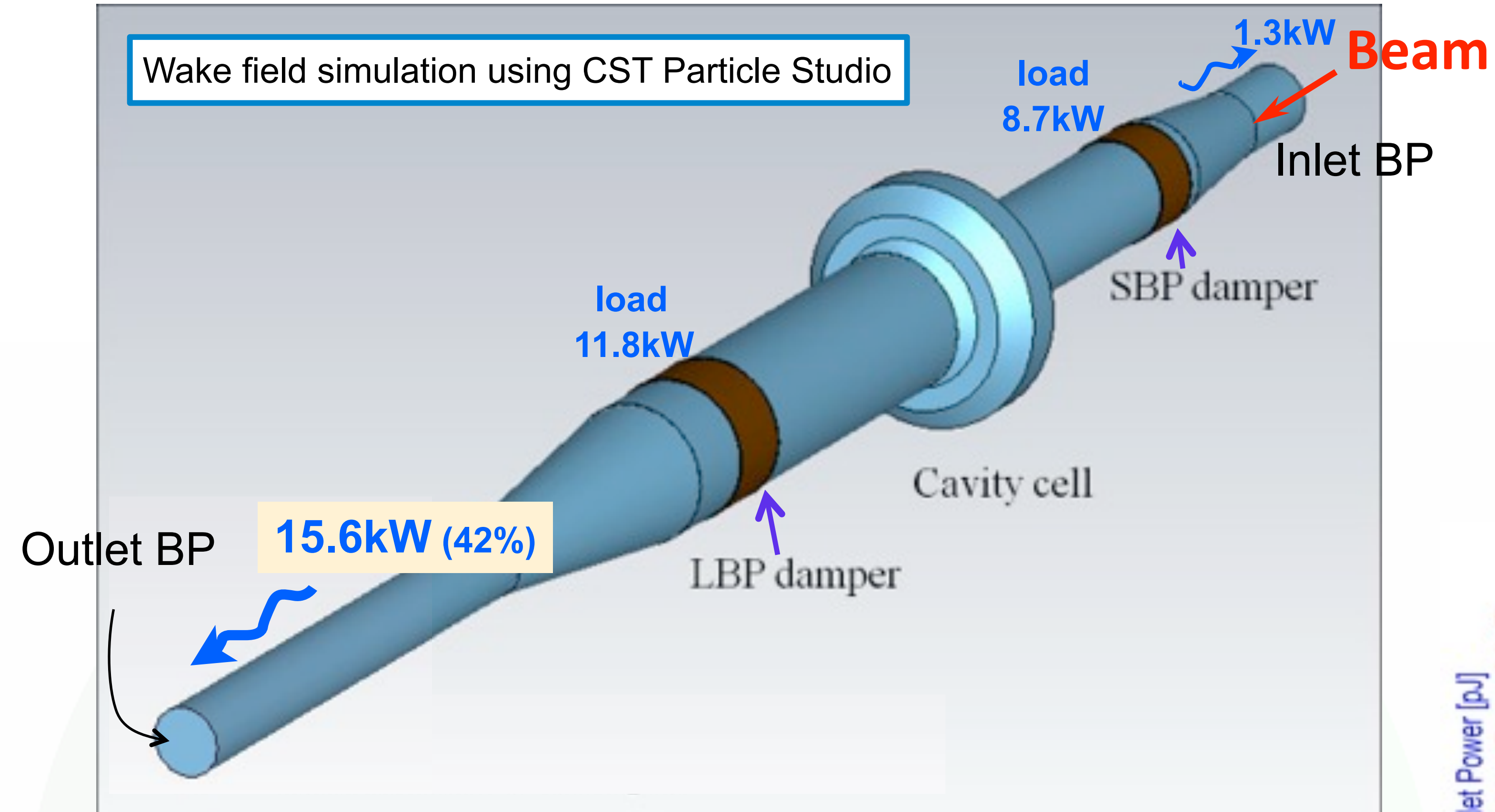
In design parameter, the HOM power is calculated as 37 kW/cavity. As measures against the large HOM power, the additional SiC damper was studied.

We have a lot of use-experiences of SiC, and SiC has several advantages such as low-outgas, mechanical strength, easy treatment, .. etc.

SCC-HOM parameters	KEKB (achieved, calc.)	SuperKEKB (design, calc.)
Beam Current	1.4 A	2.6 A
Bunch Length	6 mm	5 mm
Bunch Charge	10 nC	10 nC
Loss Factor	1.2 V/pC	1.4 V/pC
HOM power	**17 kW/cavity**	**37 kW/cavity**

<Topic>
SCC

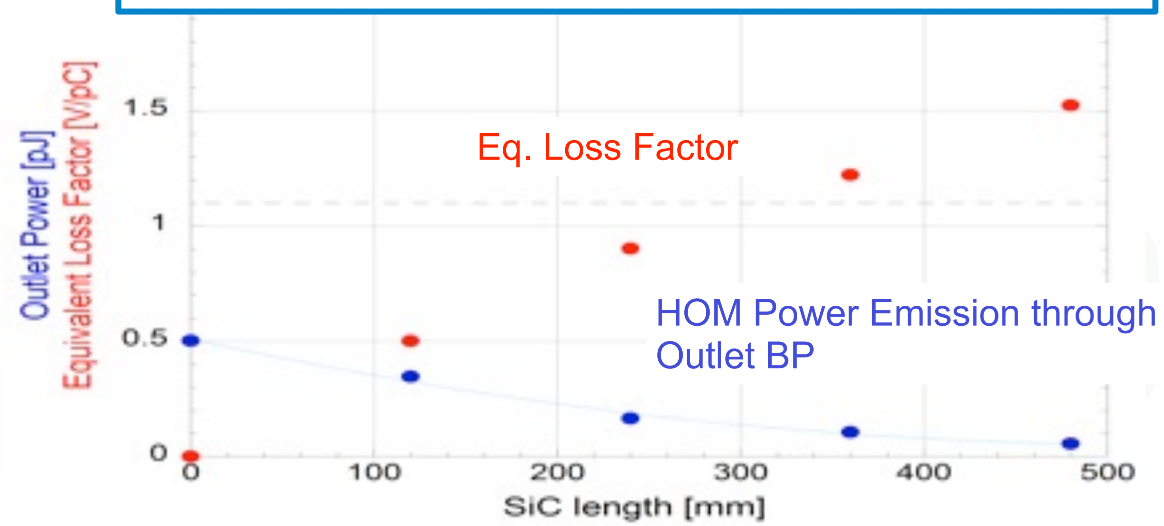
Simulation Study of Additional SiC Damper



According to calculation using CST particle studio with wakefield solver, existing damper (LBP, SBP) loads are not large, but emission power through the outlet beam pipe toward the downstream cavity becomes to be large, 15 kW.

	Without SiC		With SiC (240mm)	
	Eq.LF [V/pC]	HOM Load [kW]	Eq.LF [V/pC]	HOM Load [kW]
Total	1.38	37.4	1.94	52.5
Inlet BP	0.05	1.3	0.05	1.5
Outlet BP	0.58	15.6	0.20	5.4
SBP	0.32	8.7	0.34	9.2
LBP	0.44	11.8	0.44	12.0
SiC 240mm	--	--	0.90	24.4

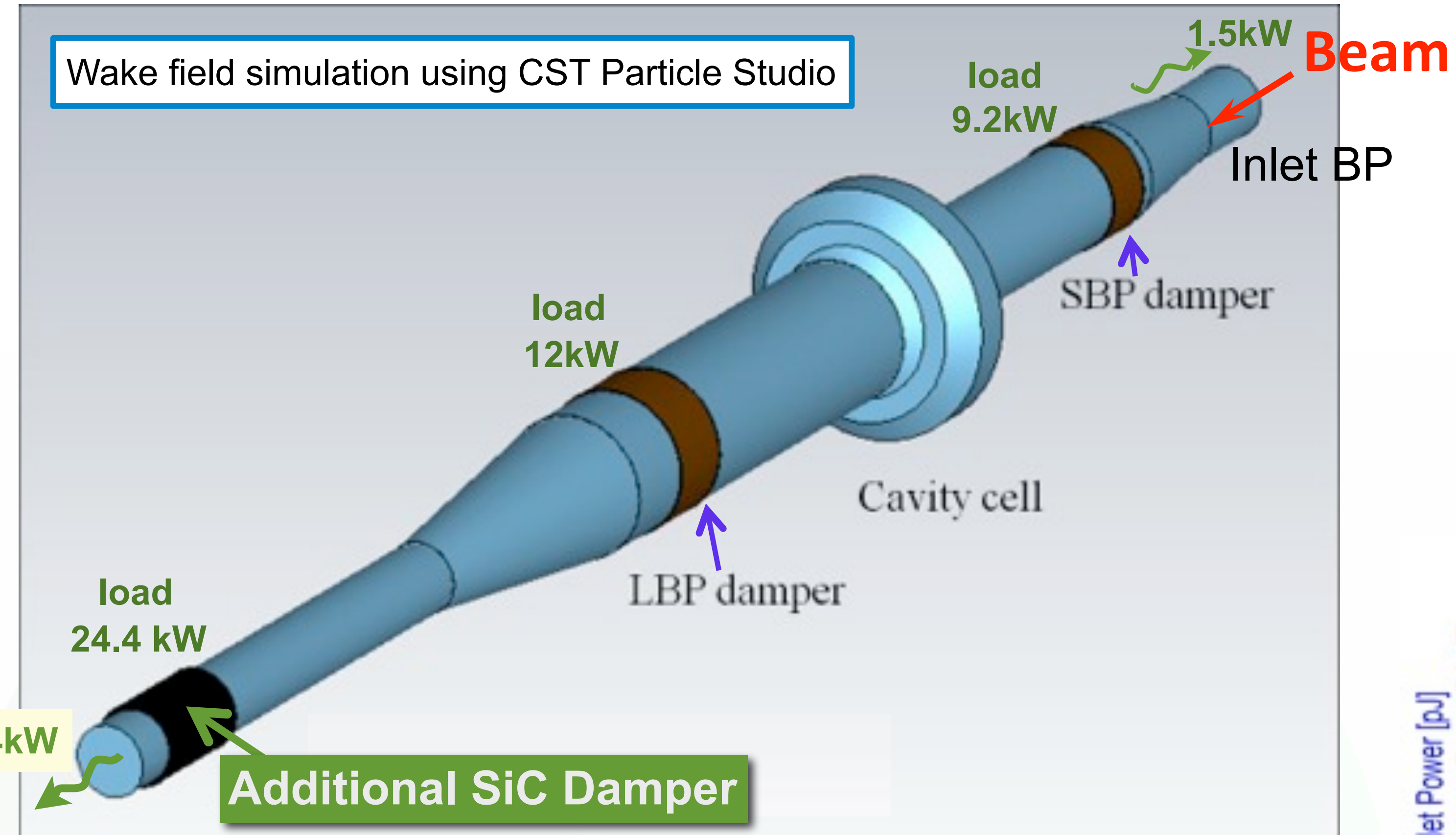
Eq.LF and Emitted Energies vs SiC Length



The emission power can be reduced to 1/3 by the additional damper. The load of existing dampers is not increased.

Additional damper can absorb more HOM power emission as the length becomes longer. In our practical condition, 240 mm is suitable length.

Simulation Study of Additional SiC Damper



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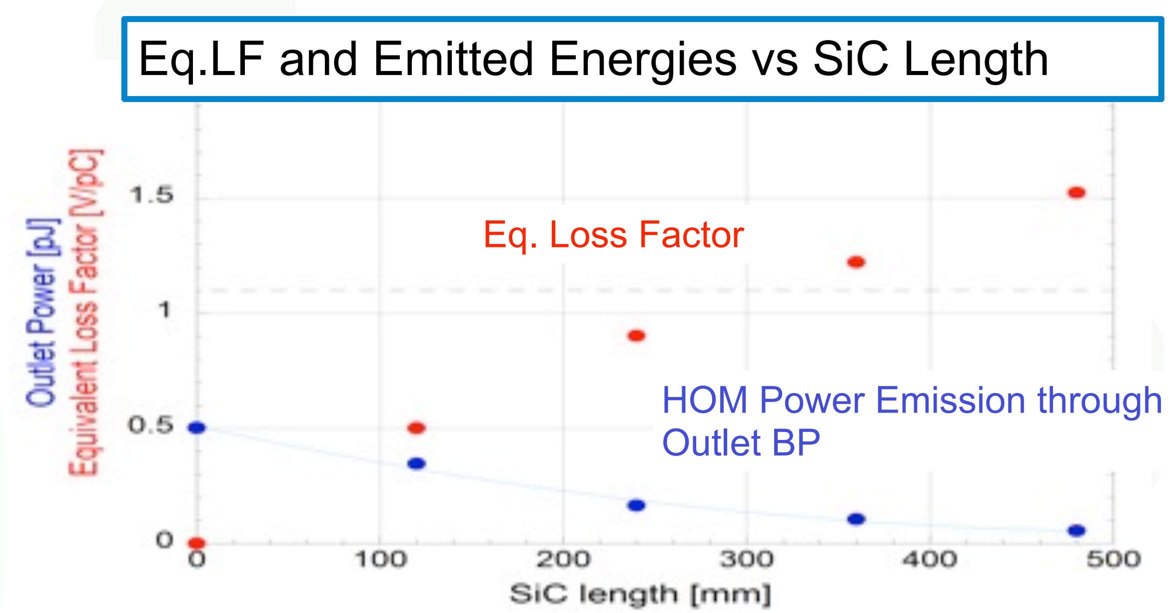

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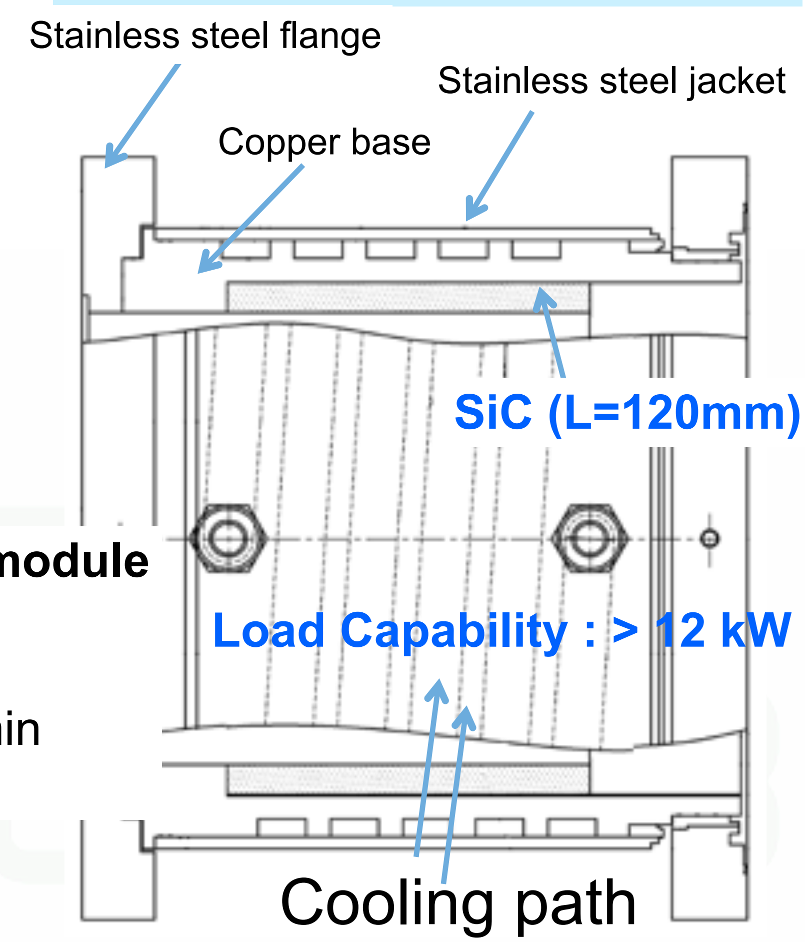
<Topic>
SCC

Development of Additional SiC Dampers

New SiC damper modules were developed for SCC module. The SiC absorber length is 120 mm, therefore, two damper modules are needed for one SCC module. One SiC module needs to load 12 kW, because the expected HOM power loaded by the SiC is totally 24 kW at 2.6 A of beam current.

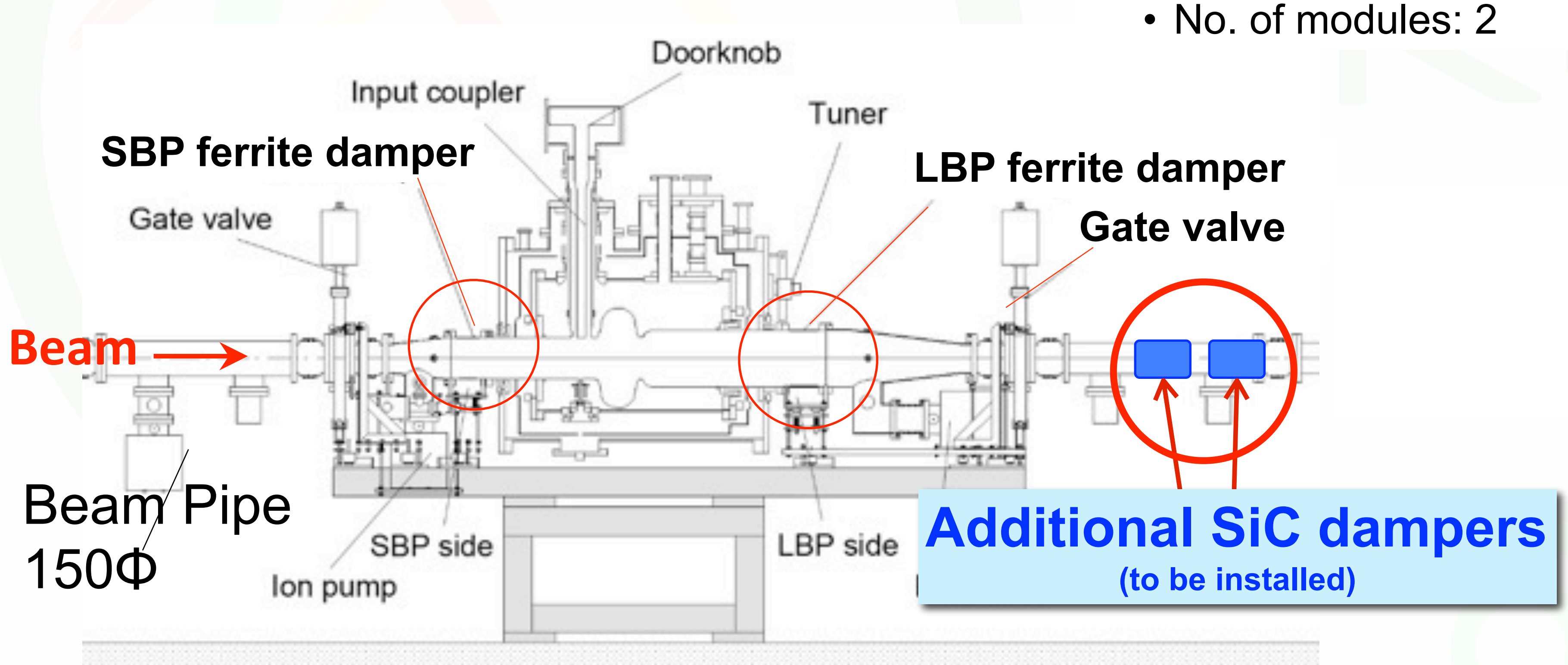
The additional SiC damper can be installed into downstream outside of gate valve of the SCC module. The cavity surfaces do not need to be exposed to the air. The risk of degradation of the cavity performance can be avoided.

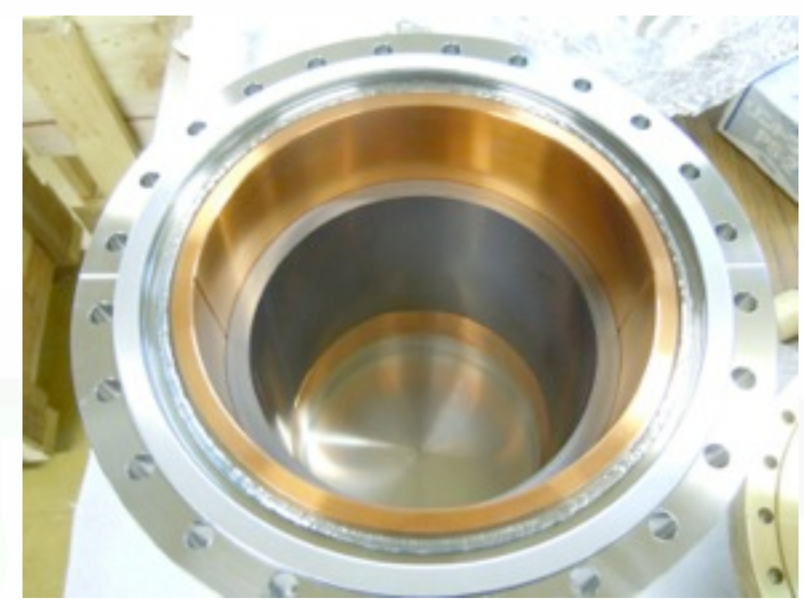
SiC damper module



- **Additional SiC damper module**
  - SiC : φ150x10x120
  - Cooing path: 5
  - Water flow rate: 15L/min
  - No. of modules: 2

- **Ferrite HOM damper (existing)**
  - SBP damper:φ220x4x120

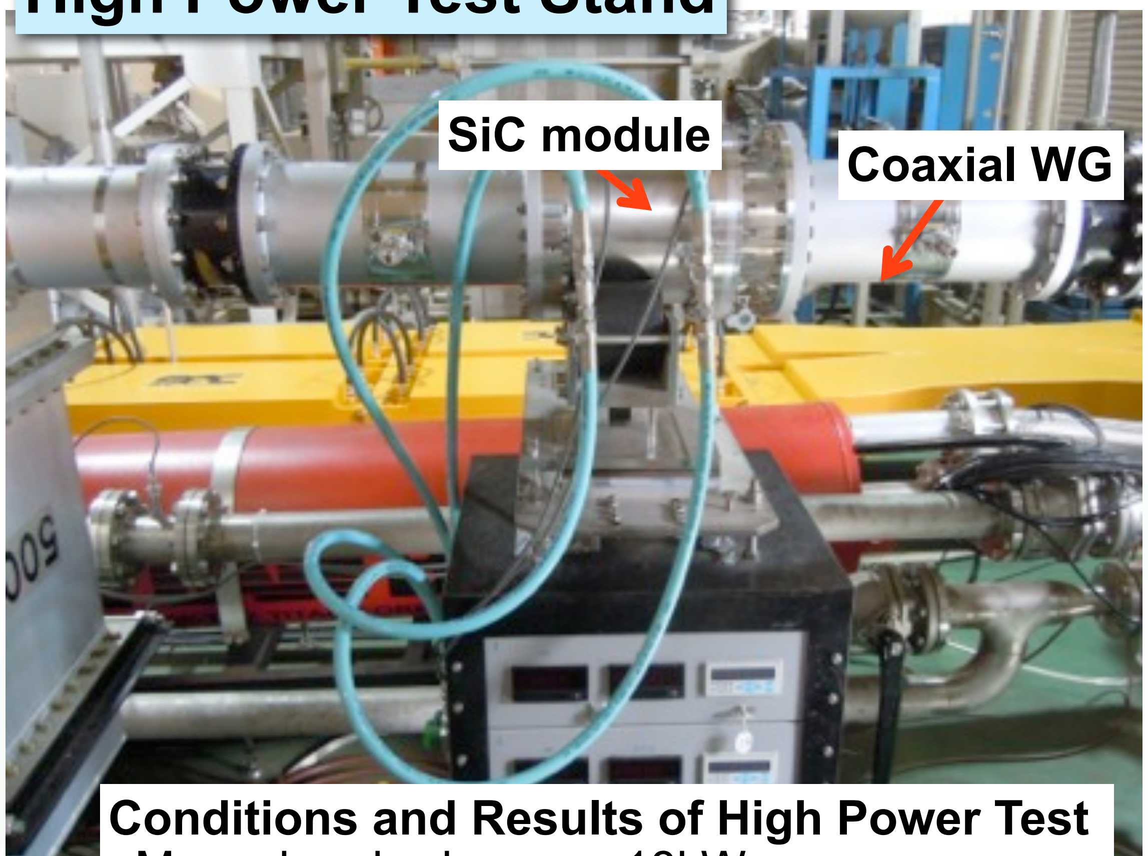




<Topic>
SCC

High Power Test Result
of the new SiC damper module

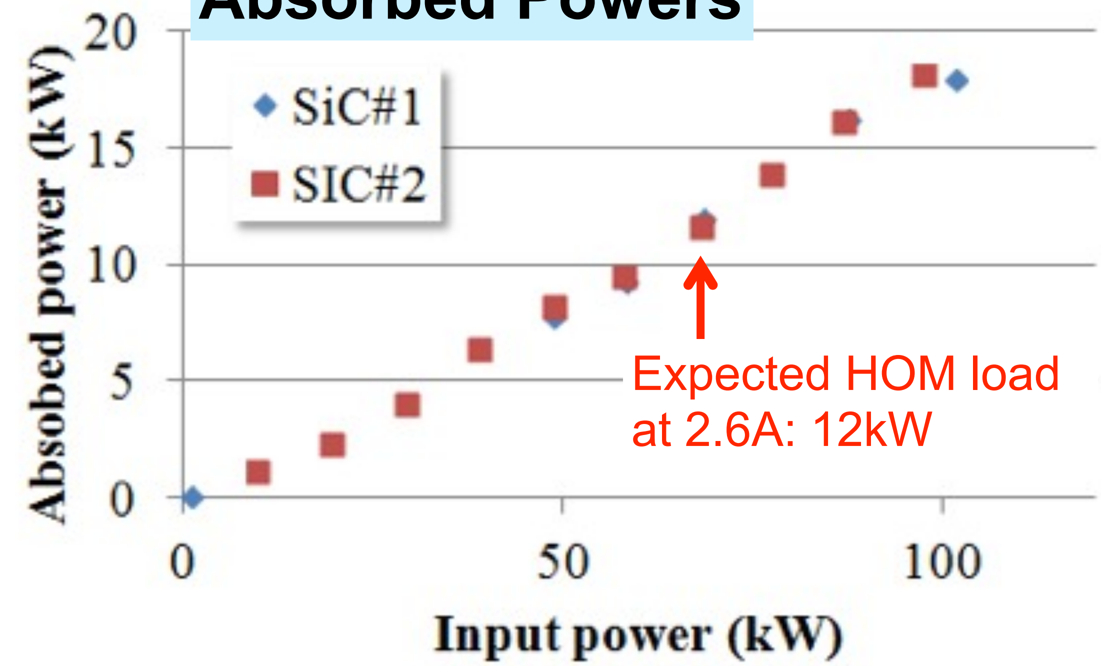
High Power Test Stand



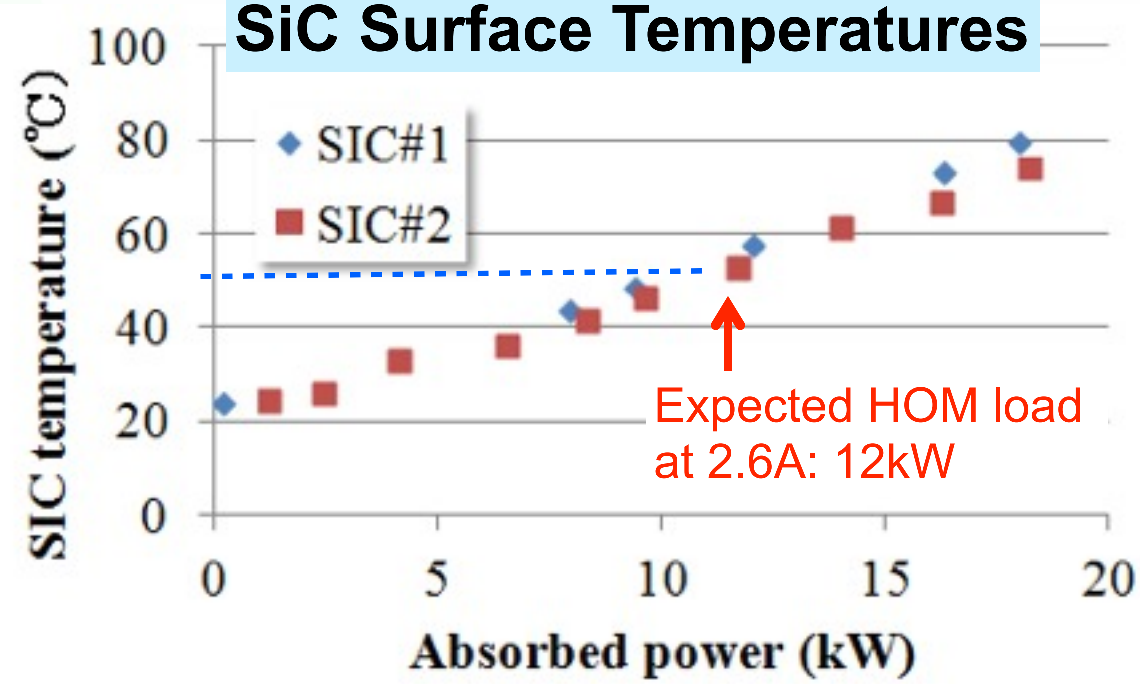
Conditions and Results of High Power Test
- Max. absorbed power: 18kW
- Max. SIC temperature: 80 ℃
- Max. flange temperature: 60℃
- Cooling water: 15L/min
- Inlet temperature: 25℃
- Outlet temperature: 42℃

12 kW/module of absorption power, that is expected HOM load, was achieved in enough low SiC surface temperature.

Absorbed Powers



SiC Surface Temperatures



Conclusion:
We have established the new SiC HOM damper modules with adequate load performance for SuperKEKB !
Those modules will be installed into the beam line for confirmation of practical HOM damping effect.

High Power RF System

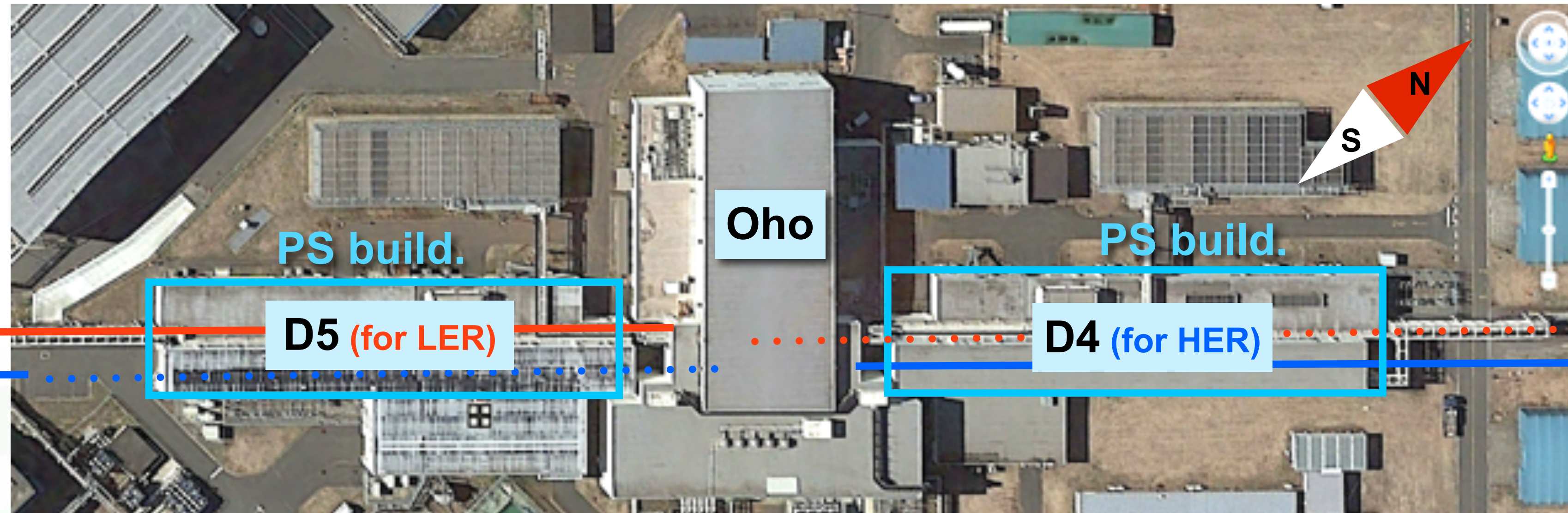
Klystron
Kly. Power Supply
Waveguide system

<Topic>
HPRF

High Power RF System
(above-ground part)

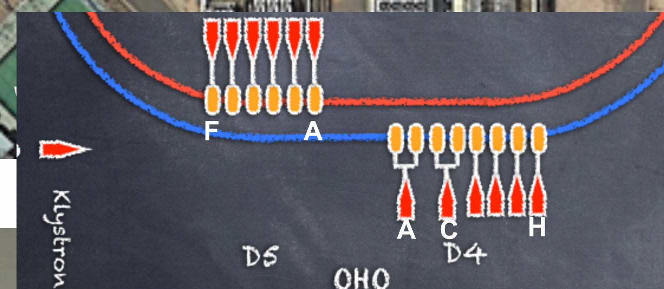
to Fuji

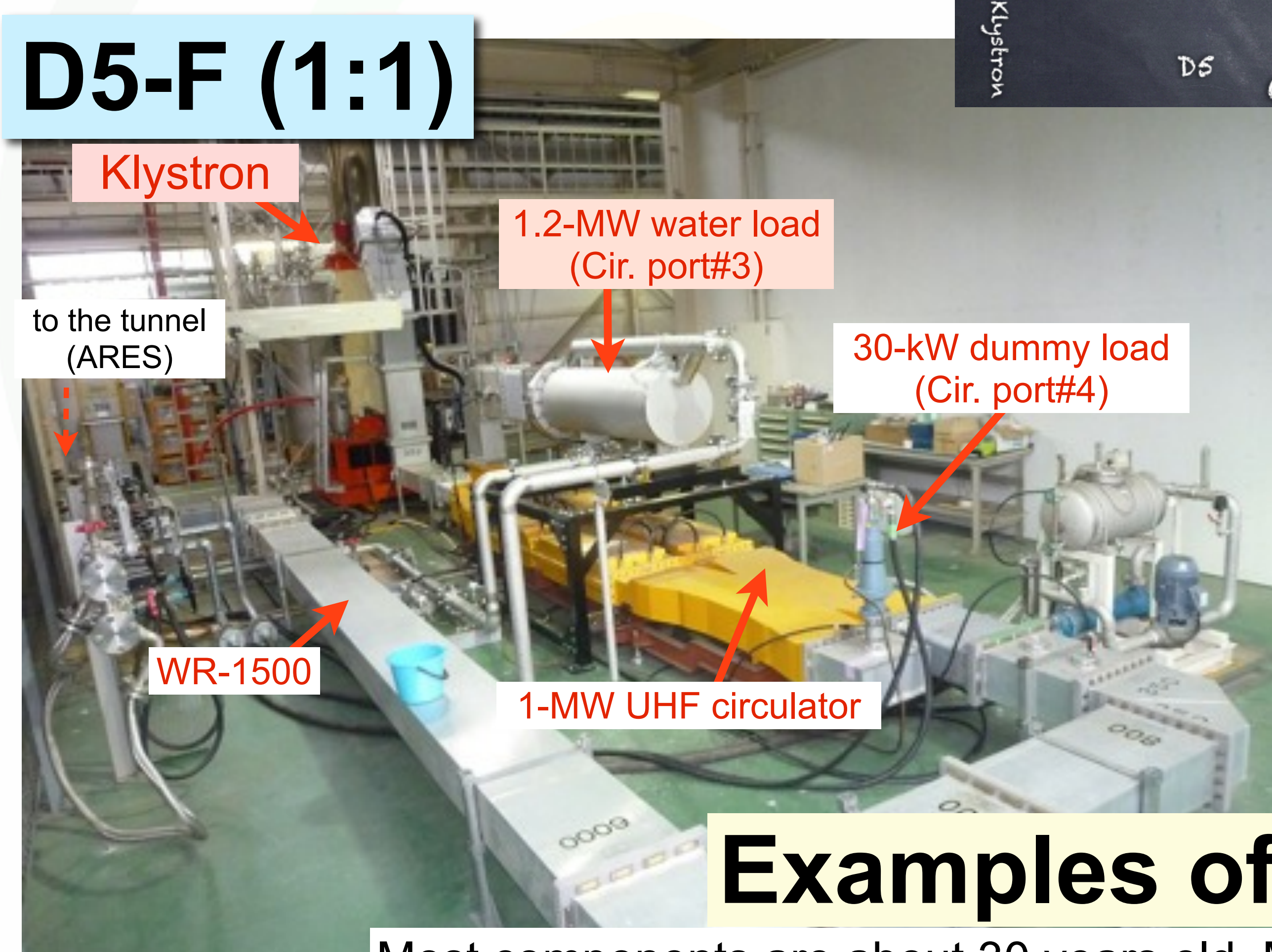
+e

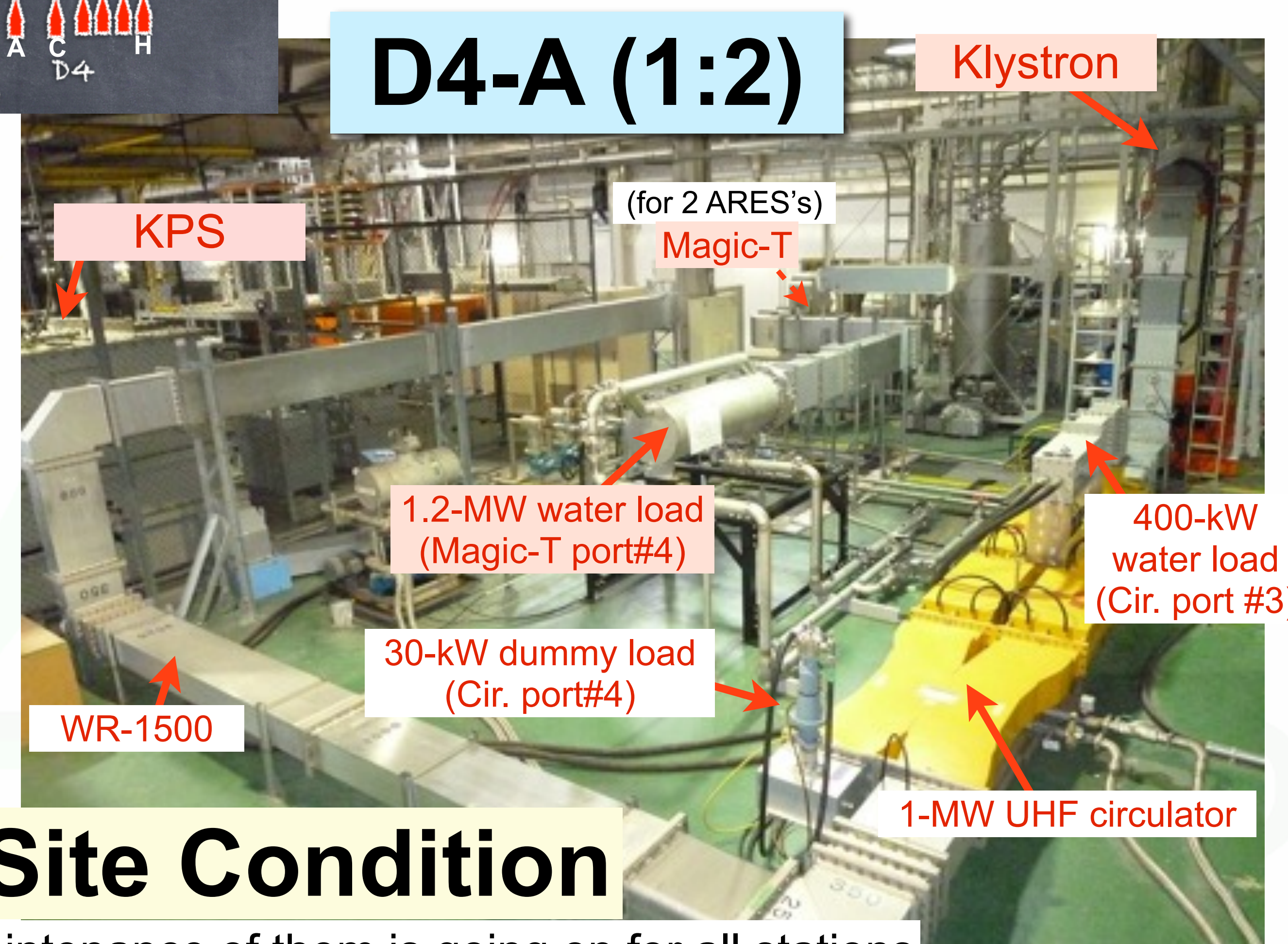


to IP

-e





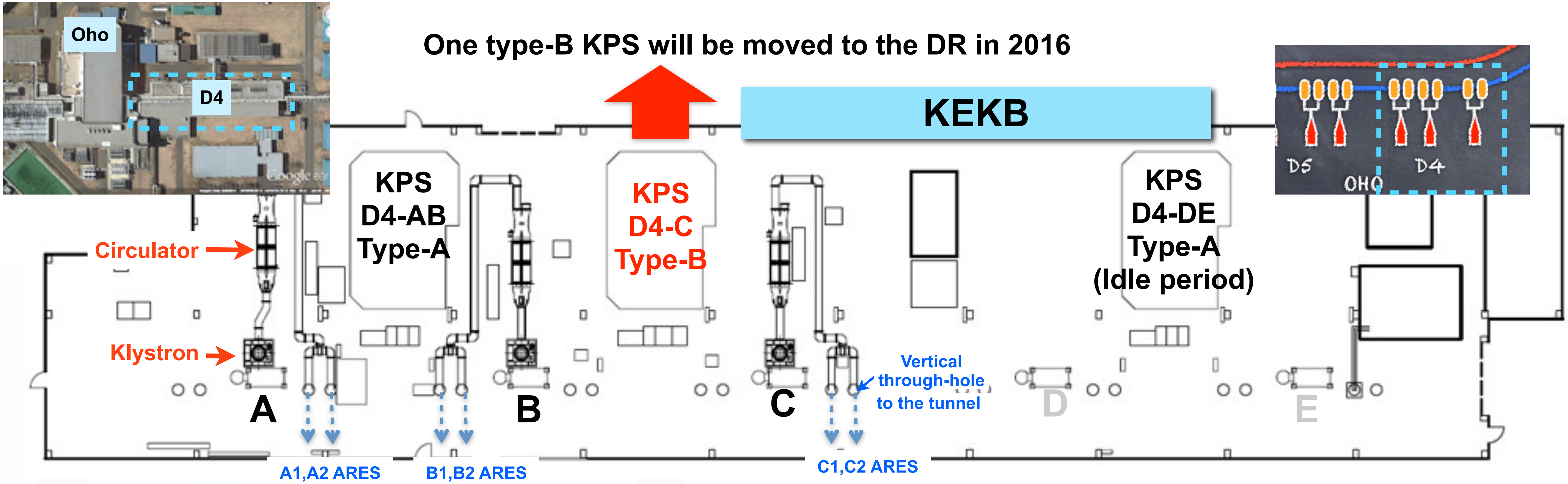


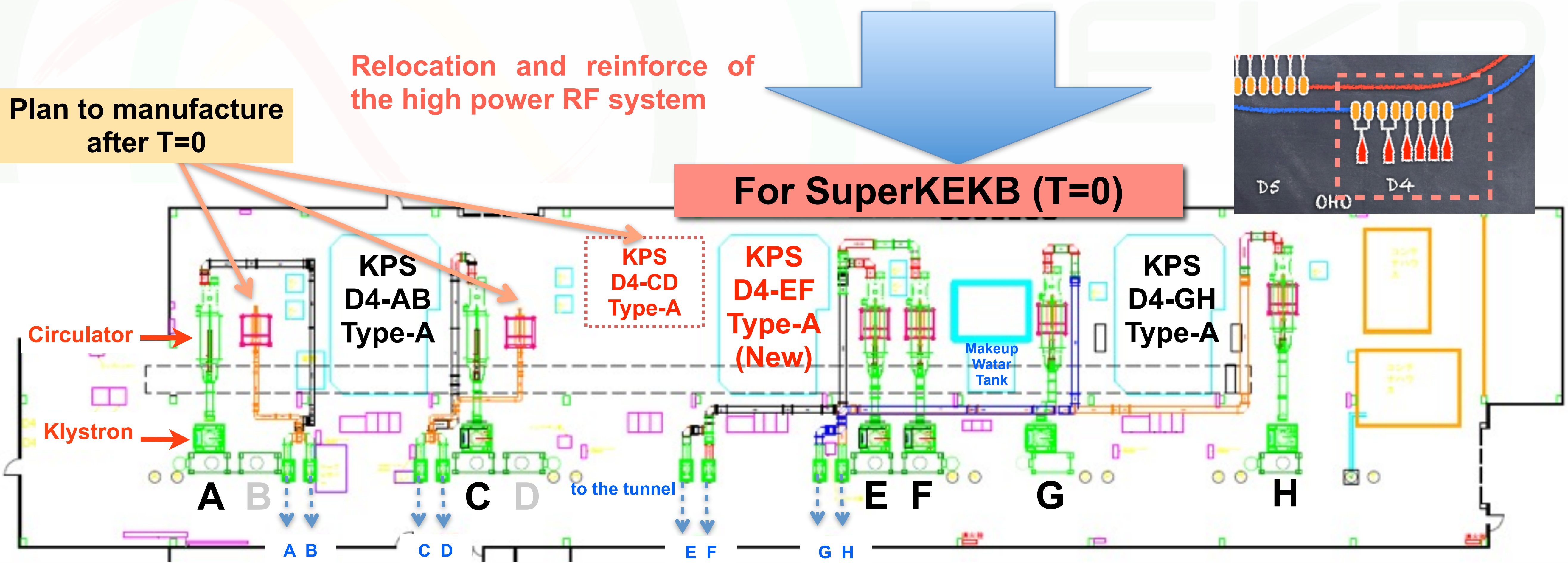
Examples of Site Condition

Most components are about 30 years old. Maintenance of them is going on for all stations

<Topic>
HPRF

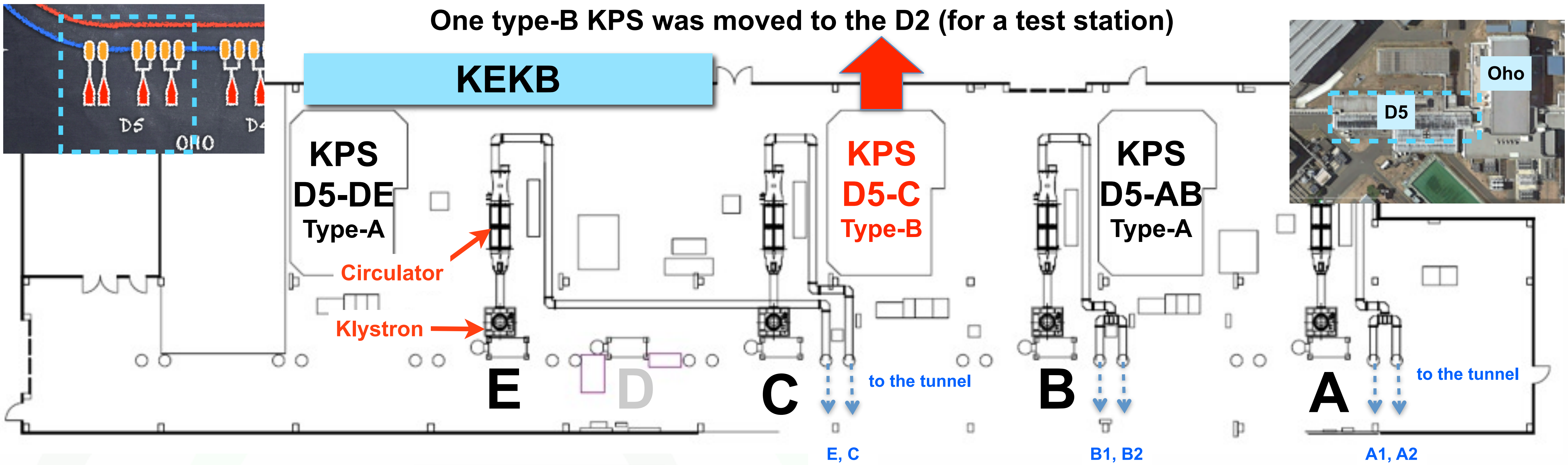
Reinforcement @ Oho D4





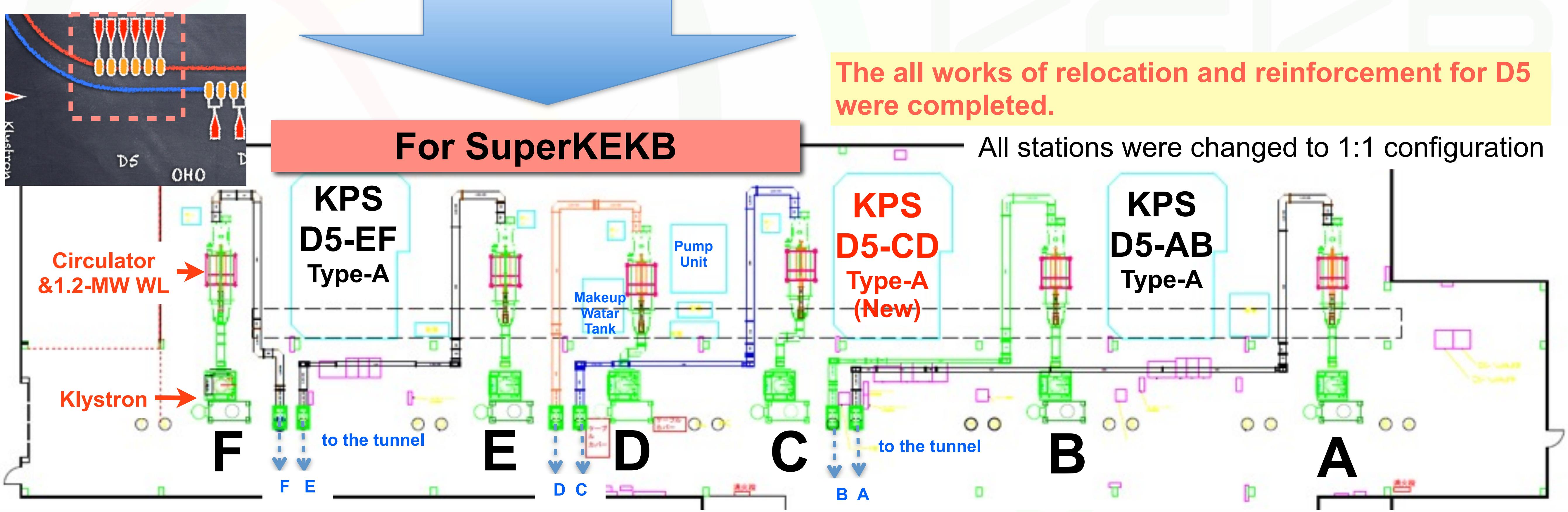
<Topic>
HPRF

Reinforcement @ Oho D5



The all works of relocation and reinforcement for D5 were completed.

All stations were changed to 1:1 configuration



<Topic>
HPRF

Status & Plan of HPRF System (Summary)

Klystron

: Klystron set up (D4: +3, D5: +2, D10: exchange for Toshiba) : finished
: Manufacture of the cooling system for the reinforced stations (D4, D5) : finished

KPS (Klystron Power Supply)

: Additional Two power supplies set up for the reinforced stations (D4-EF, D5-CD) : finished
: Maintenance for the existing power supplies (D4, D5, D10, D11) : finished
(D7, D8) : will be finished in October 2015

High-power components

: Connection of the waveguide system : will be finished in March 2015
: Manufacture of new 1.2 MW water loads (D4: 6, D5: 6 -> total 12) : finished
→ set up to the stations : finished

: Overhaul of the existing 1.2 MW water loads (19 loads) : finished
→ replaces to the stations : will be finished in June 2015
: Manufacture and set up of the 30 kW dummy loads (25 units) : finished
: Manufacture of the cooling system for the 1.2 MW water loads (D4, D5): finished
: Maintenance of 1MW UHF circulators : will be finished in August 2015

**Other maintenance work: will be finished in October 2015 **

Addition and relocation for reinforcement were almost completed.

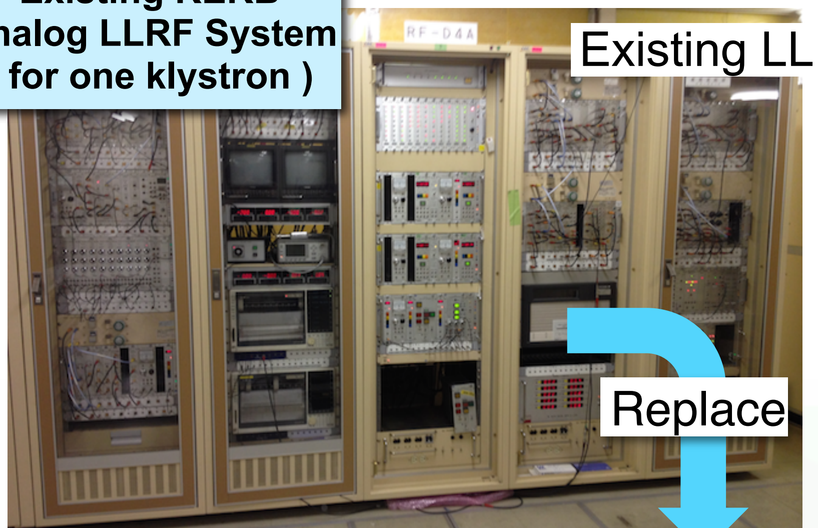
High power RF system will be all done well in advance of operation start.

Low Level RF Control System

New LLRF Control System

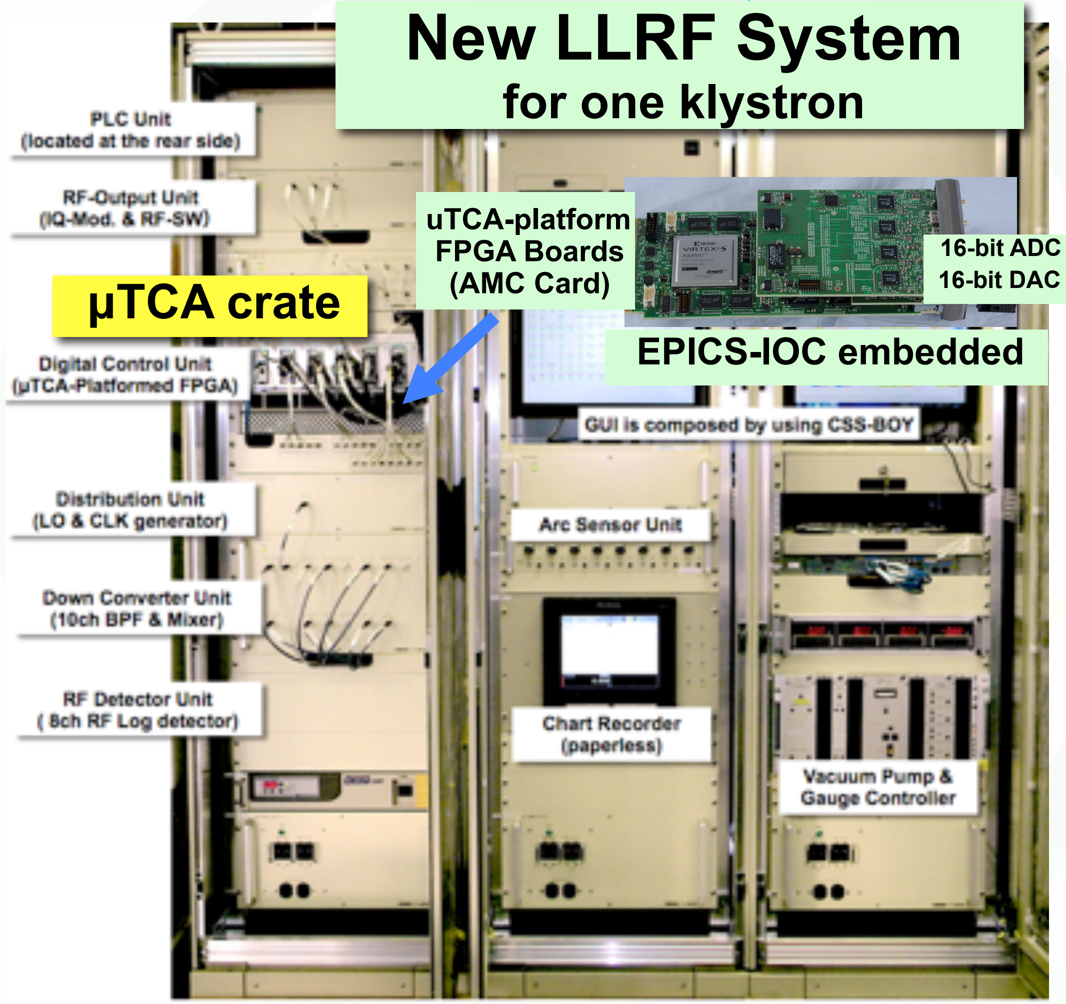
has been developed for higher accuracy and flexibility.

Existing KEKB Analog LLRF System (for one klystron)



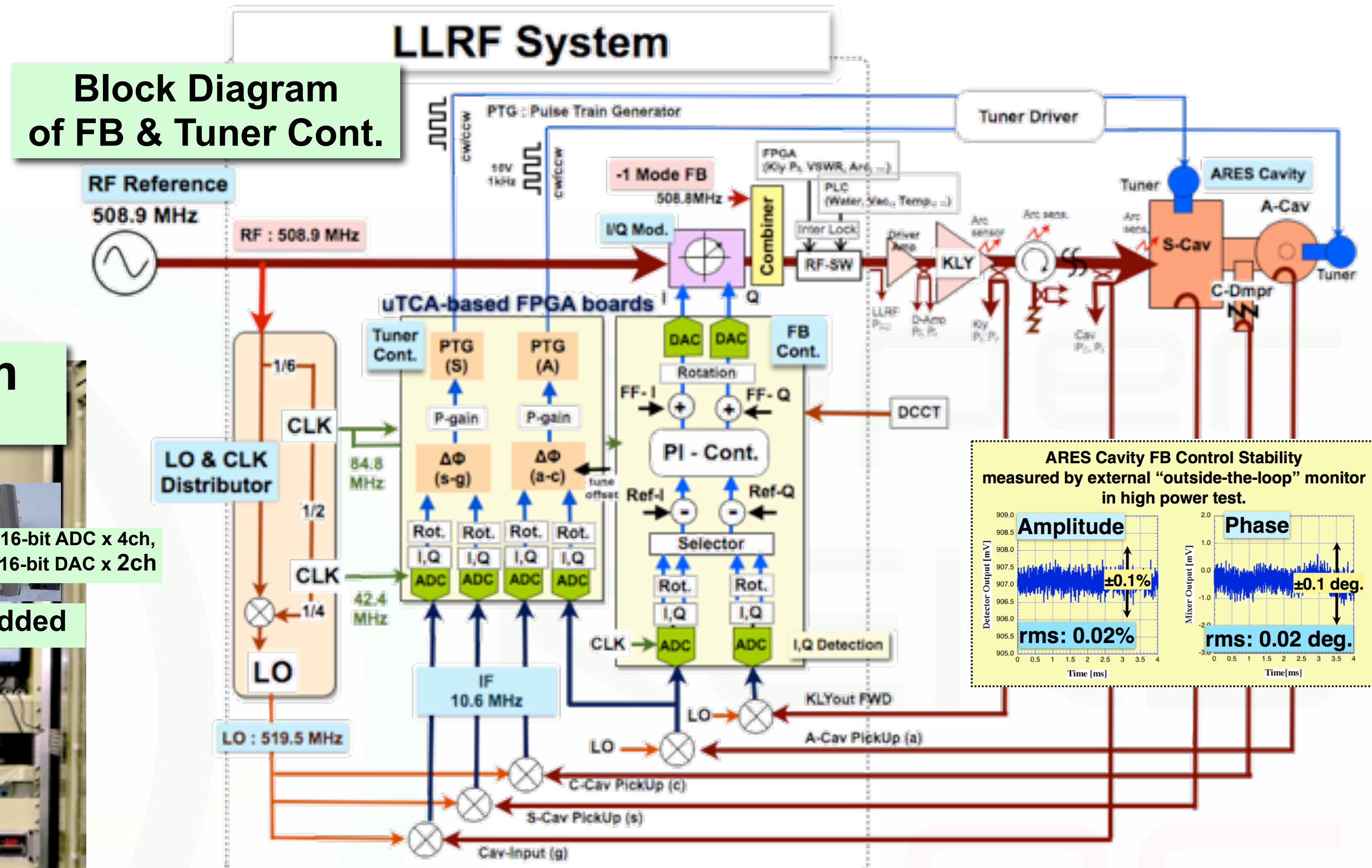
Existing LLRF controls systems will be replaced with new ones step-by-step.

New LLRF System for one klystron



- Consisting of μTCA-platformed FPGA boards (AMC), & PLC.
- EPICS-IOC with Linux-OS is embedded in each of them.
- Common hardware for both of ARES & Superconducting Cavity.
- Klystrons (LLRF) : Cavity unit = 1 : 1 (SuperKEKB)

Block Diagram of FB & Tuner Cont.



The good performance was demonstrated in the high power test with ARES cavity, and the regulation stability was 0.02% in amplitude and 0.02 deg. in phase.

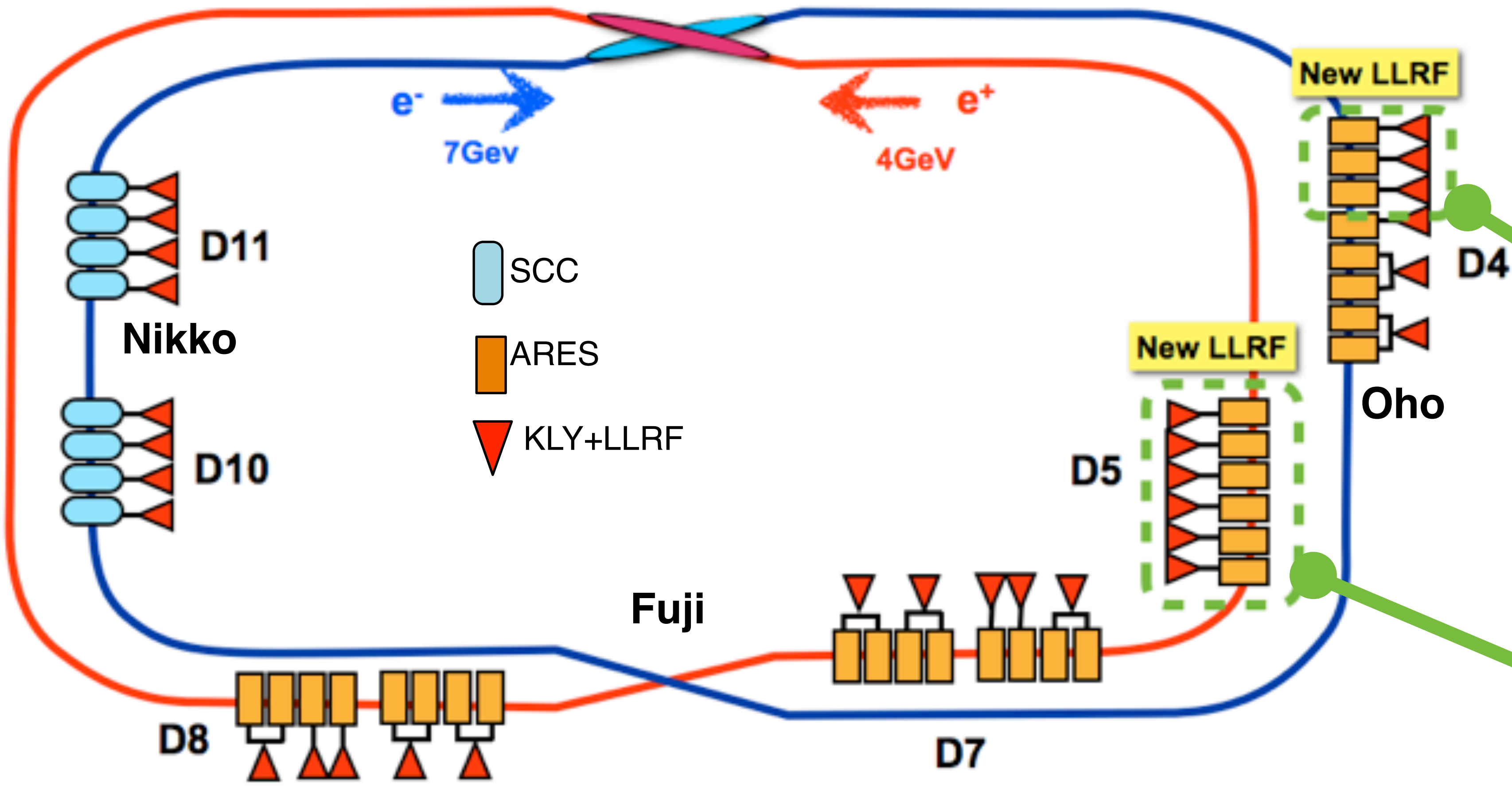
The μ=-1 mode feedback would be applied to a few or some stations. (Not to all stations)

If not enough, The -1 mode signal will be distributed to the other stations.

In the KEKB operation, the μ=-1 mode FB was applied to only one station in each ring respectively and it was enough effective.

<Topic>
LLRF

Installation Status of new LLRF



+

Status & Plan

- New LLRF control systems were installed to 9 klystrons stations at Oho D4&D5 (6@D5 + 3@D4) , and the cabling was completed.
- The other stations will be operated by existing systems in the Phase-I. D4 stations are mixing the new and old systems.
- The RF cable loss measurement and the overhaul of the old systems were also finished for all stations.
- The new operation interfaces (GUI) for the acc. operators, which integrate both the new and old systems, should be prepared before the phase-I starts.
- The DR-LLRF control system is almost the same as MR one, except 3-cavity vector-sum control is needed. It will be produced and installed in JFY2015.

<Topic>
LLRF

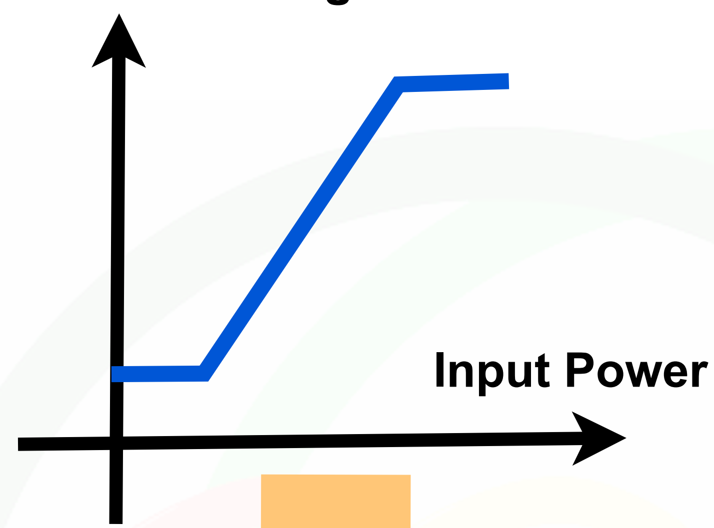
Implementation of KLY-PLL

for Compensation of KLY Phase Change due to Anode Voltage Control

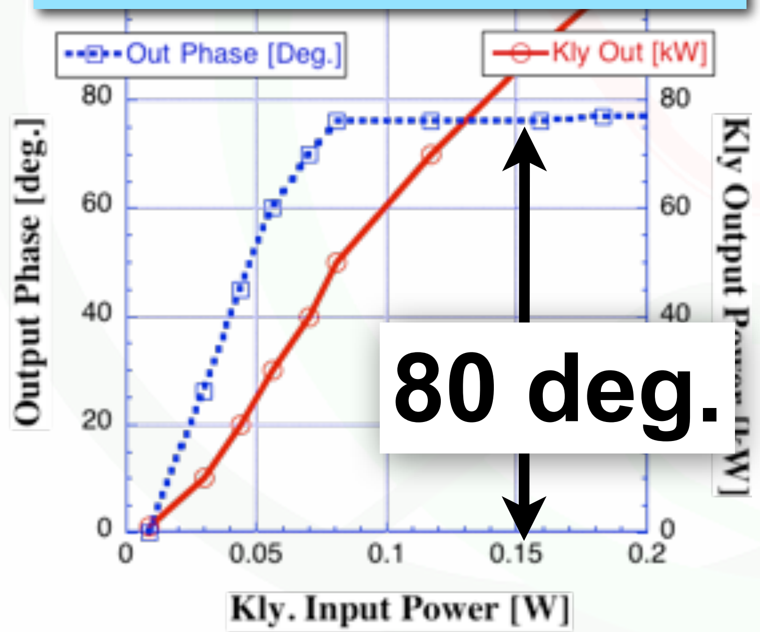
Reported ’13

For efficiency optimization, the anode voltage is controlled depending on klystron input power to reduce the collector loss.

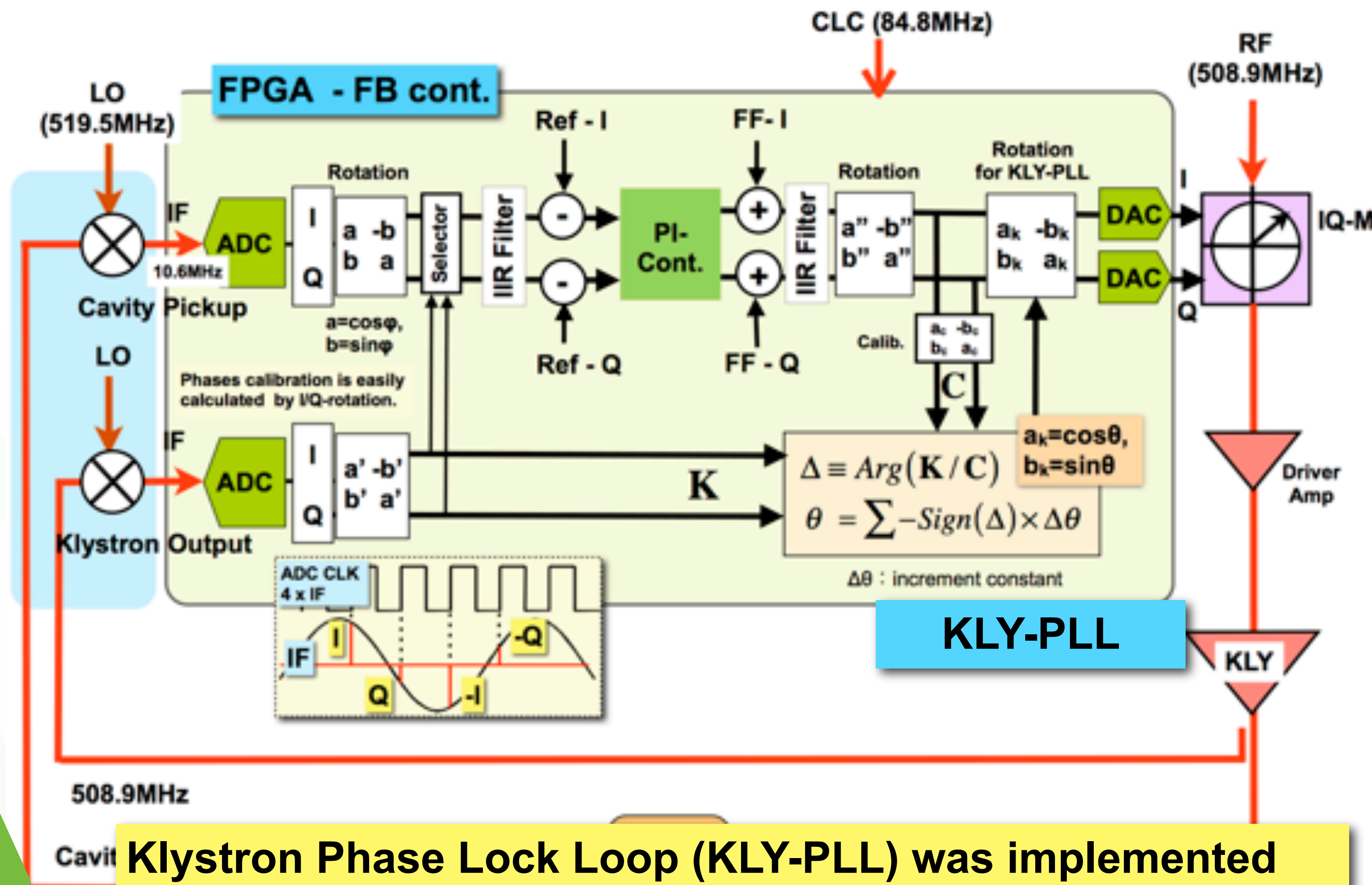
KLY Anode Voltage



Kly Input-Output Characteristics



The phase shift of 80 deg. will be critical problem for I/Q FB control technique. (Acceptable: ~60 deg.)



Klystron Phase Lock Loop (KLY-PLL) was implemented digitally in the FPGA for the cavity I/Q-FB control. (only phase compensation without KLY-AGC)

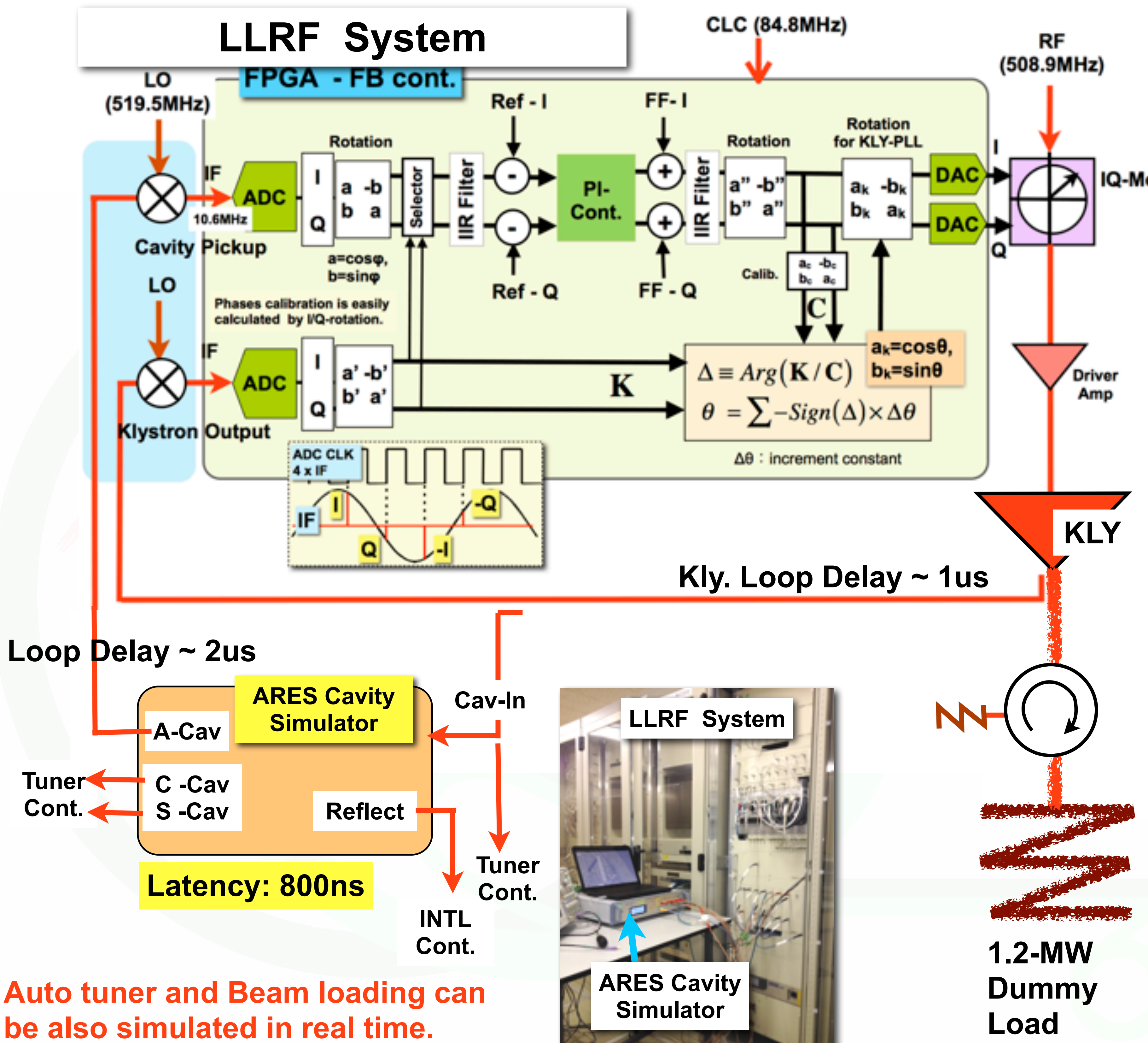
Reported ’14

The successful working was demonstrated in low level test last year, but..

Necessity for the high-power test with klystron was pointed out in the last ARC

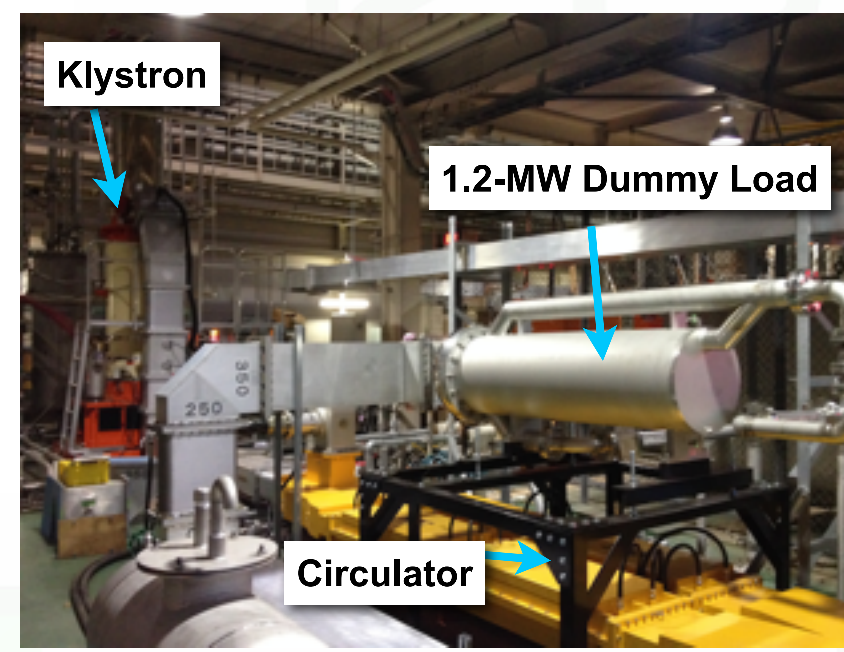
<Topic> LLRF

High Power Test @ 800 kW for the KLY-PLL control



This test was including just klystron checkup for high-power output of 800 kW.

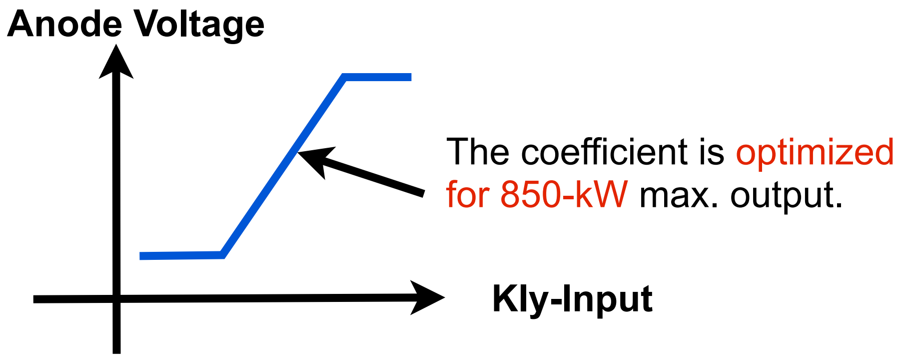
It was the first time to output over 800-kW since the KEKB operation closed.

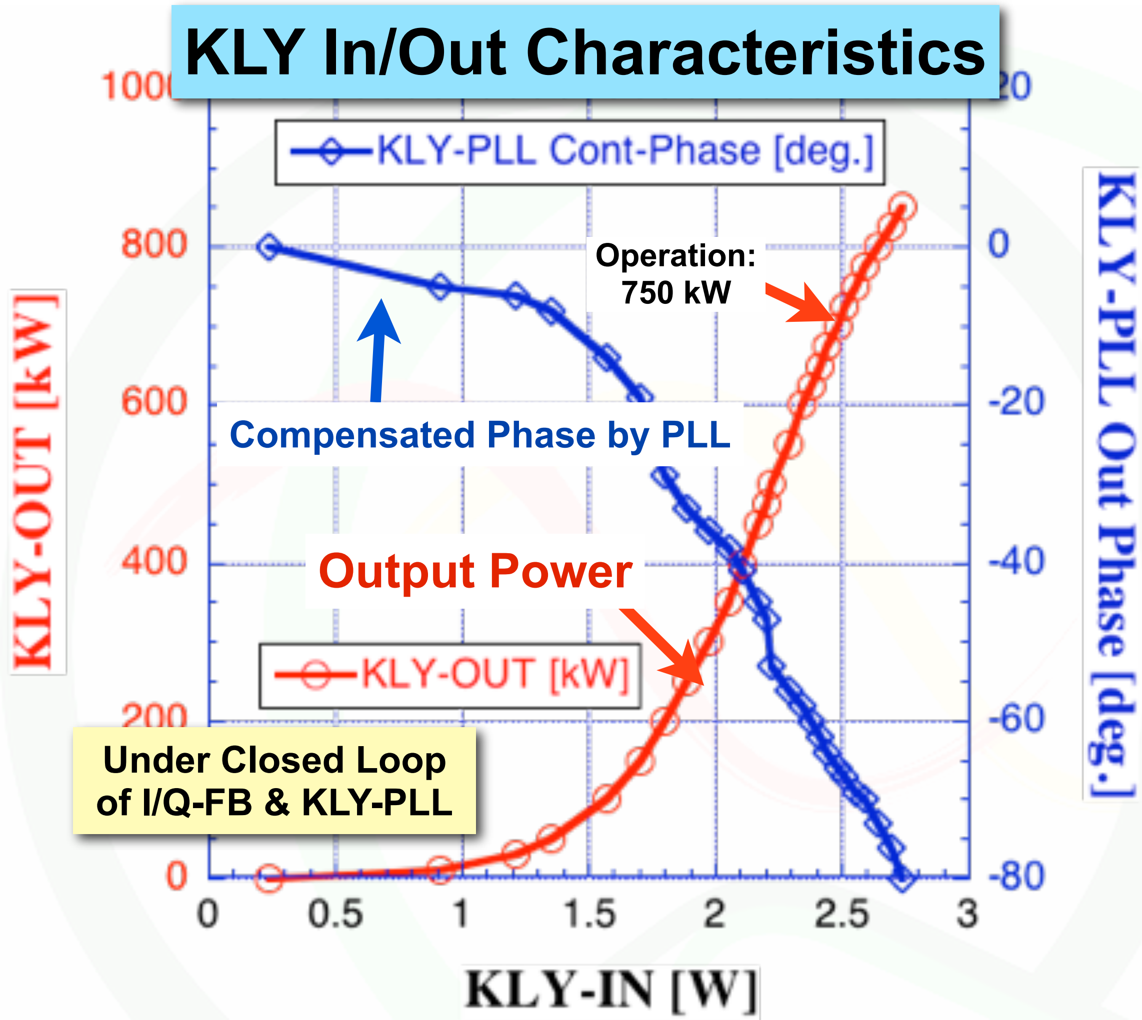


Auto tuner and Beam loading can be also simulated in real time.

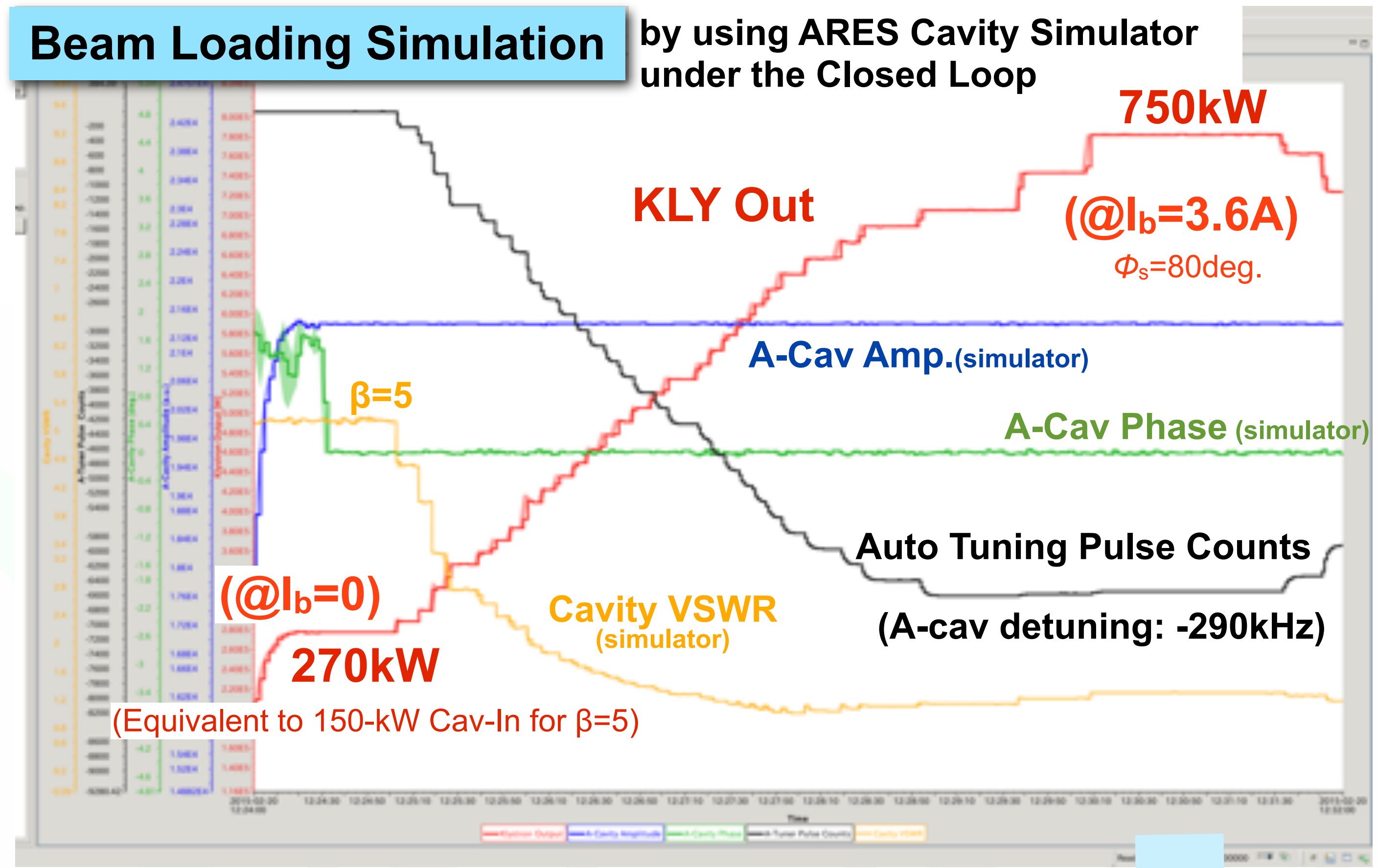
<Topic>
LLRF

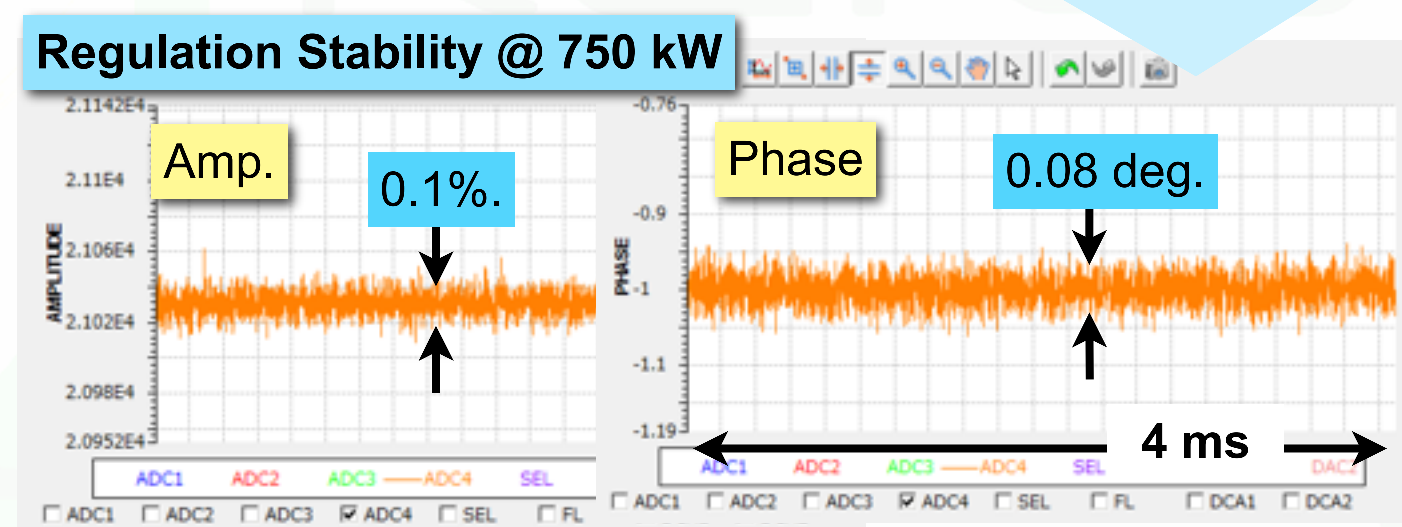
High Power Test Results
of the KLY-PLL and cavity FB control using ARES cavity simulator





Klystron linearity & gain is very good in the operation range.





KLY-PLL worked successfully over 800-kW output range, and no problem was found in the cavity FB control.

Summary

The rearrangement and reinforcement of components are almost completed for Phase-I. The remaining works to do will be done in advance of the RF conditioning start in 2015.

1. ARES Cavity

- Relocation has been completed.
- 13 input couplers have been processed up to 750-800 kW.
- Upgraded input couplers has been installed for all ARES's of D5 stations
  - ➡ Upgraded input couplers will be installed for D4 stations of the one-to-one configuration, beforeT=0 .

2. DR-Cavity

- High Power Test of the Cavity No.2 was done, and the good performance as equivalent to that of the No.1 was demonstrated.
  - ➡ The two cavities will be installed in the DR tunnel 2016. (V_c=1.4MV can be supplied.)
- The fabrication of the No 3. depends on the budget (The need for the No.3 is unclear).

3. Superconducting Cavity

- Additional HOM damper is required, then new SiC absorber was developed to reduce HOM-power emission.
- Good performance of the new HOM damper was verified by the high power test.
  - ➡ The new HOM dampers will be installed into the beam line to confirm the effective performance in beam test.

4. High Power RF System

- Rearrangement of klystrons and the power supplies were completed.
- Manufacturing of the reinforced HPRF components were completed.
  - ➡ The remaining maintenance and connection of the waveguide system will be done in 2015

5. Low Level RF Control System

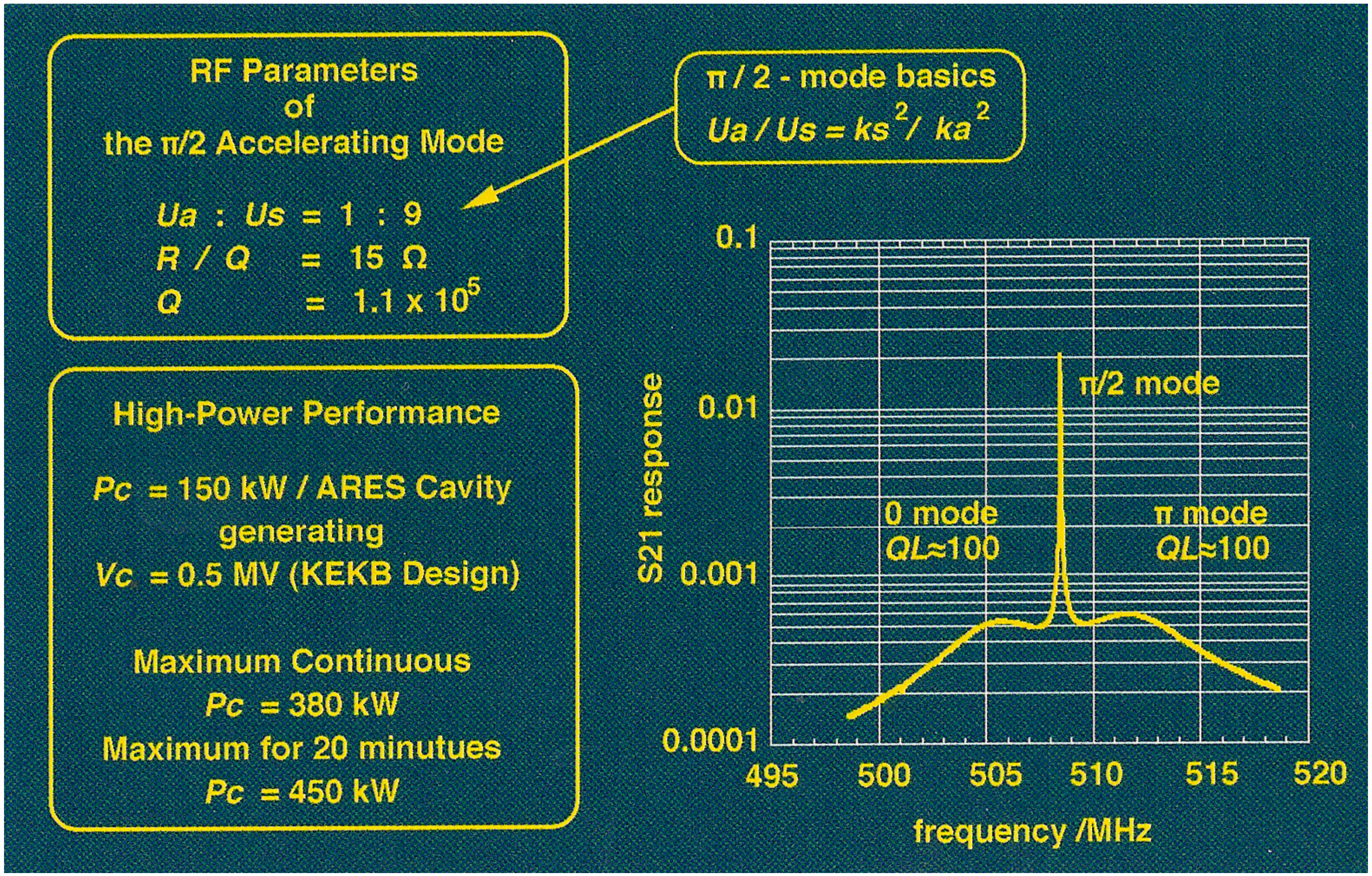
- Installation of 9 new LLRF control systems and the cabling were completed at D4 and D5. The existing systems are also used for the other stations. The LLRF hardwares for the MR are ready.
- KLY-PLL implemented in the FPGA worked successfully in the high power test.
  - ➡ For the acc. operators, new user interfaces integrating the new and existing systems should be prepared.
  - ➡ The DR-LLRF control system will be produced and installed next JFY.

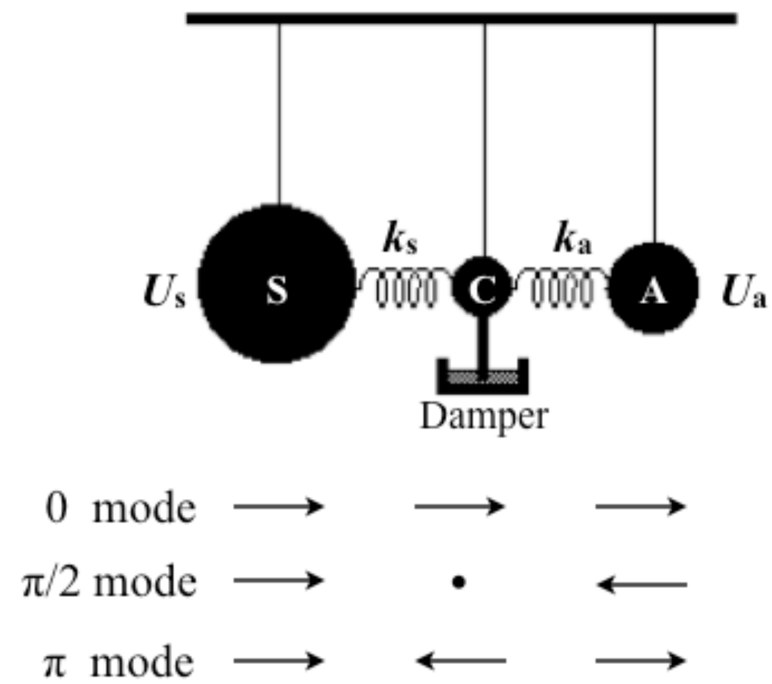
Tank you
for your attention!

Backup Slides

Fundamentals of the ARES Cavity System

T. Kageyama, 2011.02





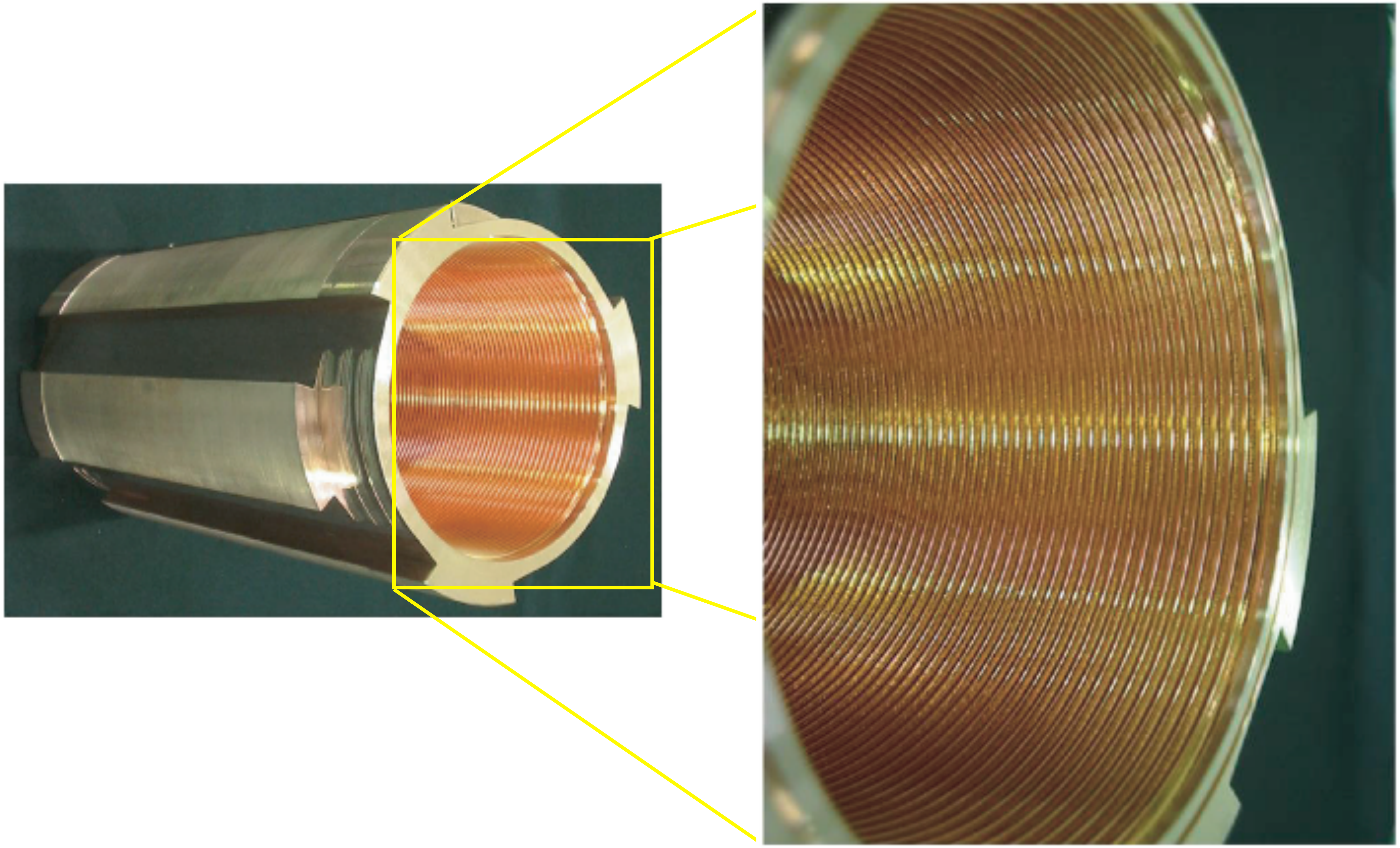
$\Delta f_{\pi/2} = \Delta f_A \,/\, (1+U_S/U_A)$

-28 kHz　-280 kHz　9

Detuning against beam loading

Flywheel Energy Ratio U_S/U_A = 9 not changed.

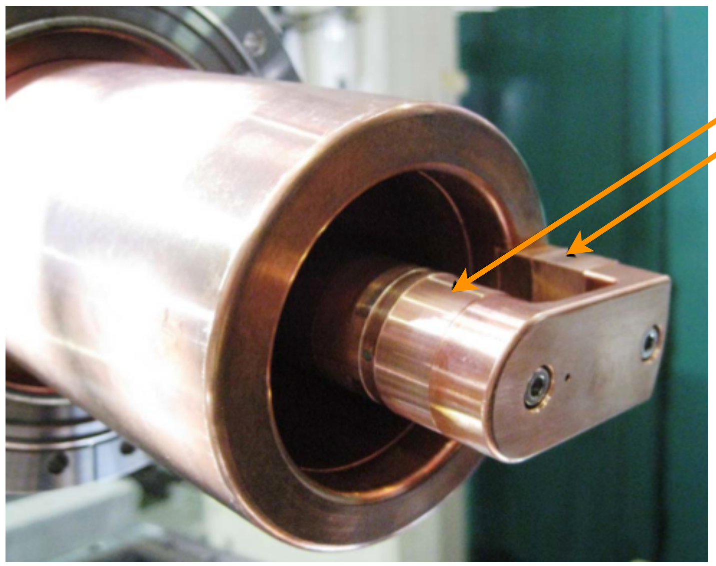
Fine circumferential grooving on the outer conductor surface in order to suppress multipactoring discharge.

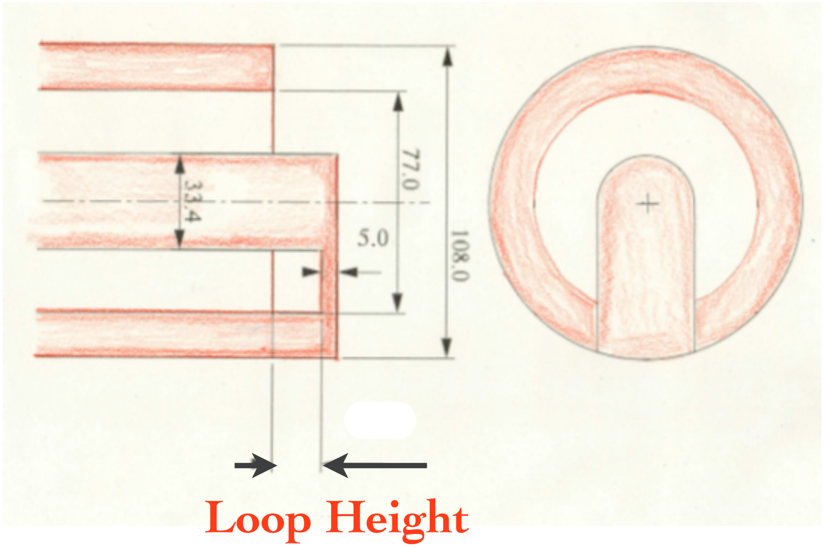


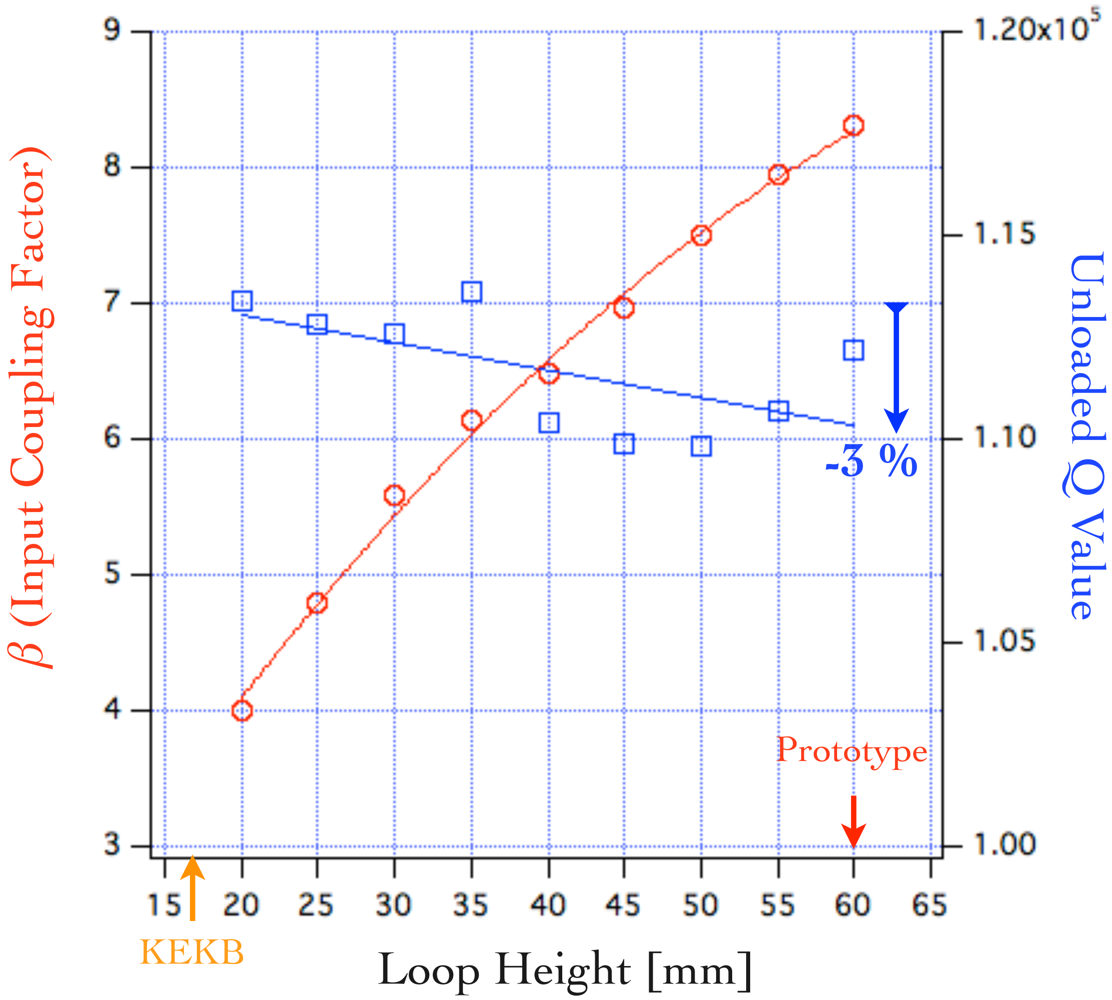
T. Abe

Successfully tested and used in actual KEKB operation.

Input Coupling Factor vs. Loop Height







K. Yoshino, H. Sakai, T. Kageyama

A prototype coupler with a loop height of 60 mm
was fabricated in JFY 2009.

Instability due to RF cavities and cure

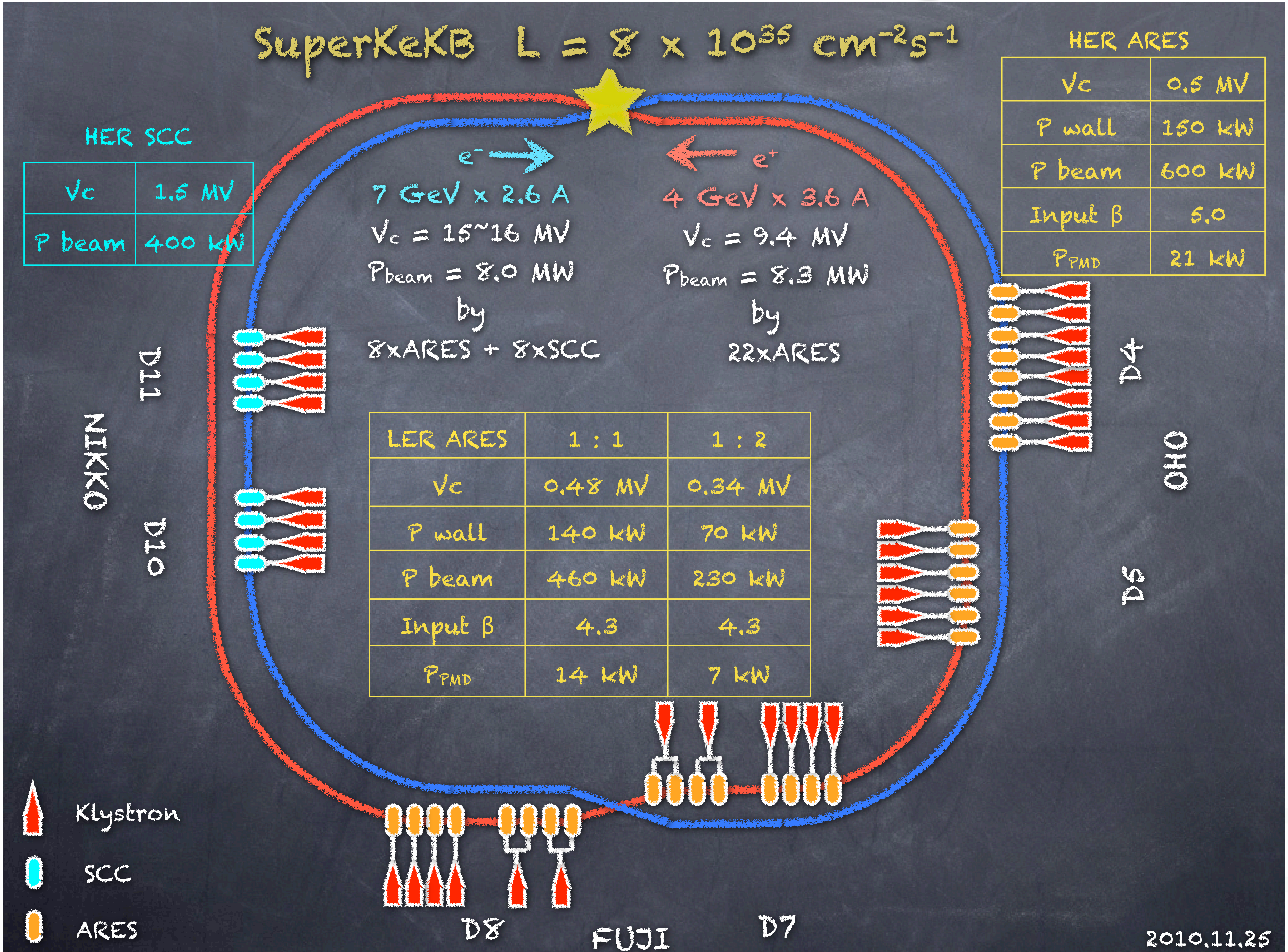
T. Kageyama, 2011.02

Ring	Longitudinal/Transverse	Cause	Frequency (MHz)	Growth time (ms)	Cure
LER	Longitudinal	ARES-HOM	1850	12	B-by-B FB
		ARES-0/π	504	21	B-by-B FB
		-1 mode	508.79	4	-1 mode damper
LER	Transverse	ARES-HOM	633	7	B-by-B FB
HER	Longitudinal	ARES-HOM	1850	59	(no need)
		SCC-HOM	1018	58	(no need)
		-1 mode	508.79	4	-1 mode damper
HER	Transverse	ARES-HOM	633	39	(no need)
		SCC-HOM	688	14	B-by-B FB

Longitudinal bunch-by-bunch FB will be needed
to suppress coupled bunch instabilities driven by RF cavities.

RF Power for Ultimate Stage

T. Kageyama, 2011.02



22 ARES Cavities operated for LER (I_b=3.6A)

T. Kageyama, 2011.02

RF frequency	508.869 MHz	
Flywheel Energy Ratio U_S / U_A	9	unchanged
Cavity Voltage V_c	0.48 MV	P(wall) = 140 kW
Detuning Frequency $\Delta f_{\pi/2}$ / Δf_{AC}	-28 kHz / -280 kHz	P(beam) = 460 kW
Input Coupling Factor β	5.0	β (optimum) = 4.3
CBI (-1 mode) due to the Acc. mode	τ = 4 ms	RF feedback
CBI due to the 0 and π modes	τ = 21 ms	bunch-by-bunch FB

HOM Power Estimation for LER

T. Kageyama, 2011.02

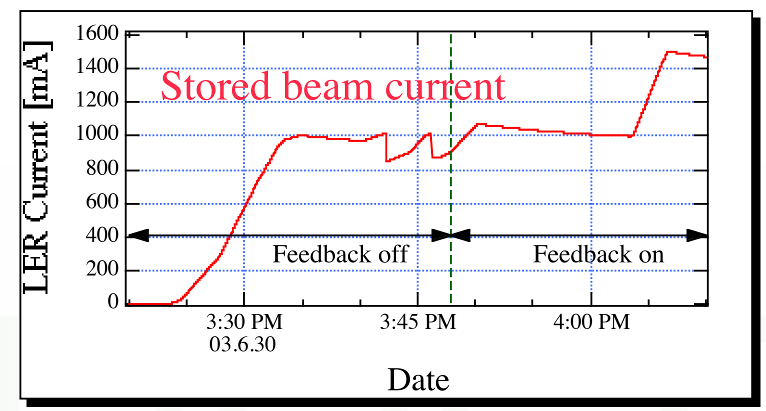
	KEKB LER Sep. 21, 2004	SuperKeKB LER	Power Handling Capability verified at 1.25 GHz	Factor of Safety
I_{beam} [A]	1.6	3.6	-	-
N_{bunch}	1293	2503	-	-
σ_z [mm]	7	6	-	-
k [V/pC]	0.40 (0.39†)	0.44	-	-
P_{HOM} /ARES [kW]	5.4†	17	-	-
P_{HOM} /HWG [kW]	1.05†	3.3	5.0	5.0/3.3 = 1.5
P_{HOM} /Groove [kW]	0.3†	0.93	1.2	1.2/0.93 = 1.3

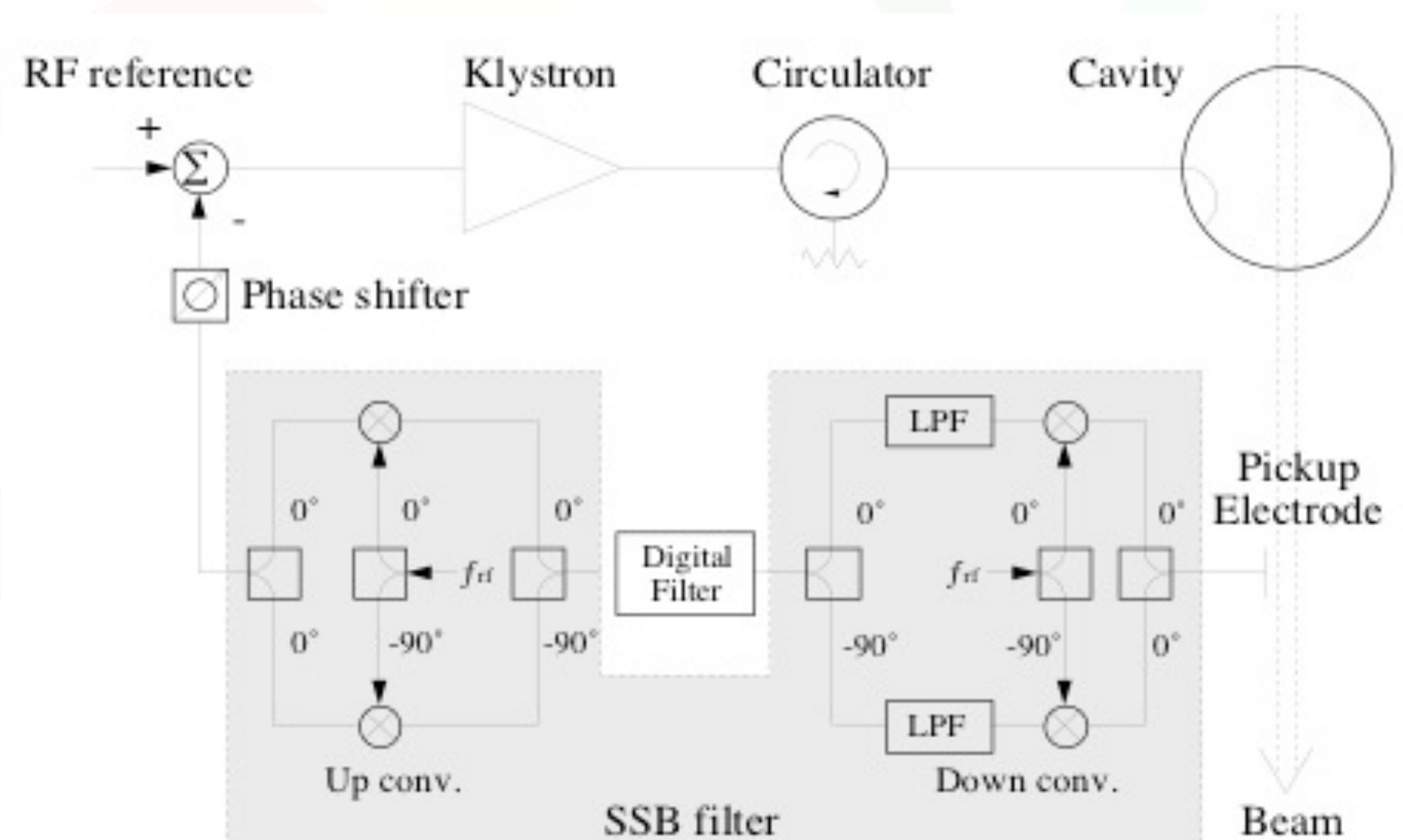
†based on calorimetric measurement

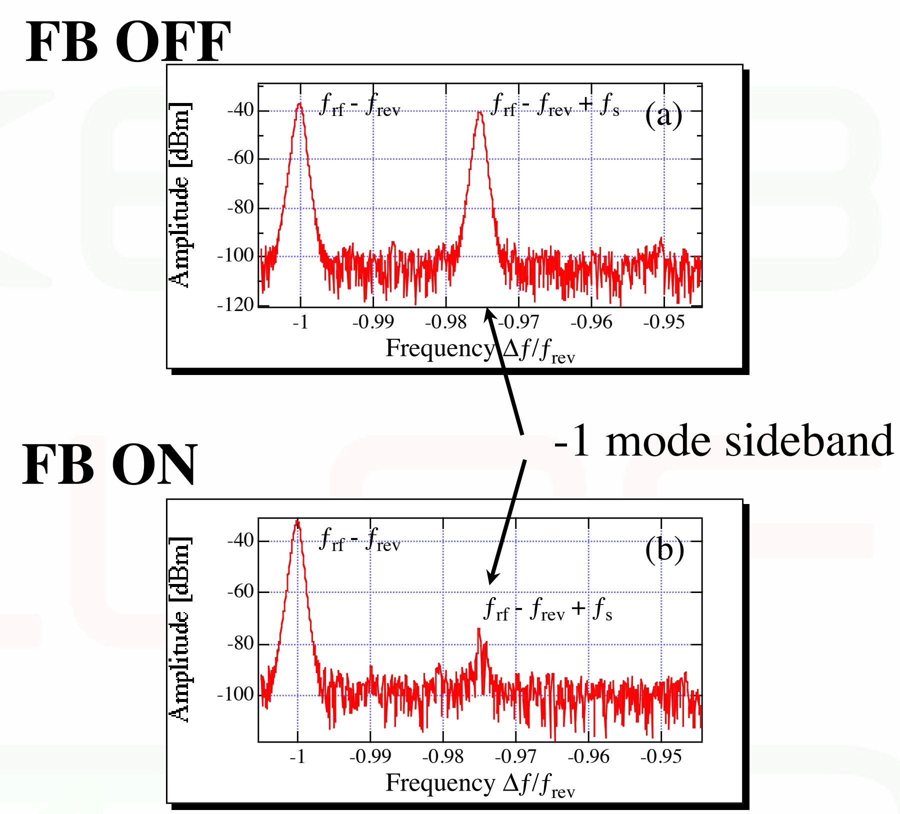
The -1 mode feedback

In the KEKB Operation

- Beam current was limited due to the -1 mode instability at 1 A in LER and 1.2 A in HER, much lower current than expected.
- The -1 mode digital feedback selectively reduces impedance at the driving frequency.
- After the -1 mode feedback was installed, the beam current could be successfully increased.







ARES Cavity Simulator

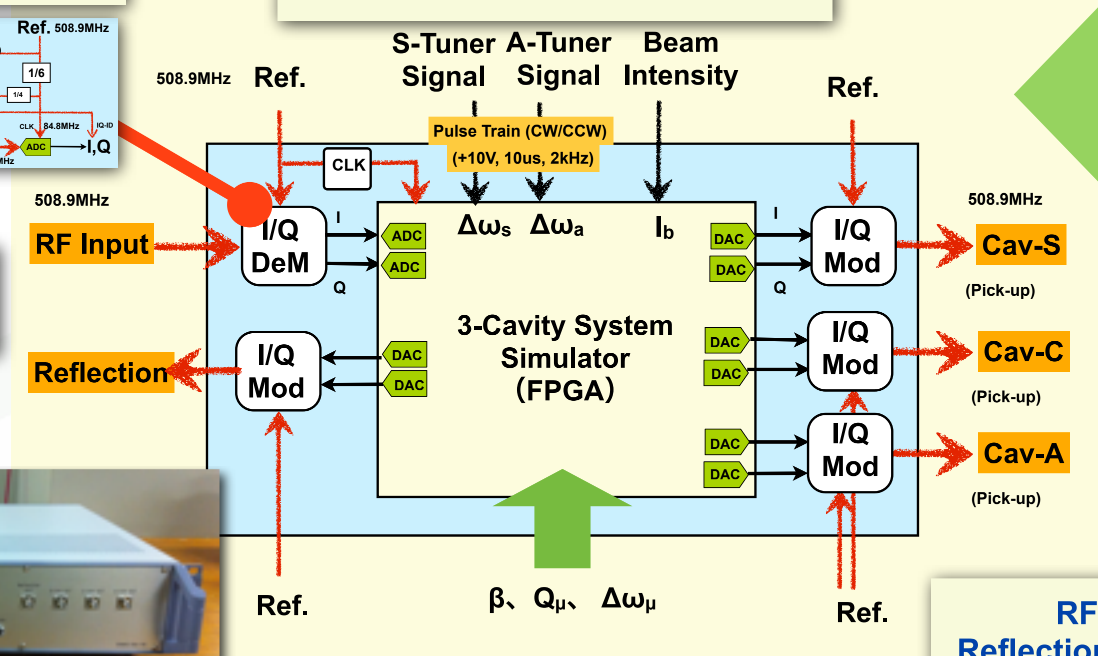
T. Kobayashi, et. al., Proc. of the 9th Annual Meeting of Particle Accelerator Society of Japan, WEPS121 (2012)

ARES Cavity Simulator

IQ-Sampling of IF Signal

Tuner control pulses (rear panel)

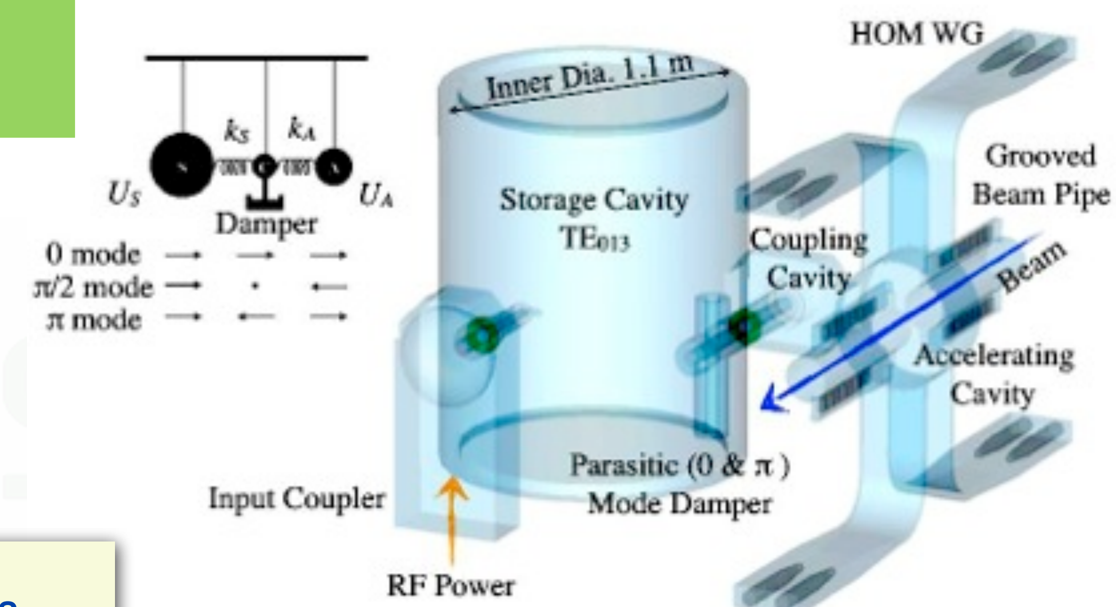
RF Input (508.9MHz)



RF Output
Reflection, A, C, S-cav.

The ARES Cavity

T. Kageyama, et. al.



A-Cav

C-Cav

S-Cav

$$
\begin{bmatrix} V_{Ar}^{n+1} \\ V_{Ai}^{n+1} \\ V_{Cr}^{n+1} \\ V_{Ci}^{n+1} \\ V_{Sr}^{n+1} \\ V_{Si}^{n+1} \end{bmatrix}
=
\begin{bmatrix}
1-\Delta t\cdot\omega_{a/2} & -\Delta t\Delta\omega_a & 0 & K_a\Delta t\cdot\omega_{a/2}Q_a & 0 & 0 \\
\Delta t\Delta\omega_a & 1-\Delta t\cdot\omega_{a/2} & -K_a\Delta t\cdot\omega_{a/2}Q_a & 0 & 0 & 0 \\
0 & K_a\Delta t\cdot\omega_{c/2}Q_c & 1-\Delta t\cdot\omega_{c/2} & -\Delta t\Delta\omega_c & 0 & K_s\Delta t\cdot\omega_{c/2}Q_c \\
-K_a\Delta t\cdot\omega_{c/2}Q_c & 0 & \Delta t\Delta\omega_c & 1-\Delta t\cdot\omega_{c/2} & -K_s\Delta t\cdot\omega_{c/2}Q_c & 0 \\
0 & 0 & 0 & K_s\Delta t\cdot\omega_{s/2}Q_s & 1-(\beta+1)\Delta t\cdot\omega_{s/2} & -\Delta t\Delta\omega_s \\
0 & 0 & -K_s\Delta t\cdot\omega_{s/2}Q_s & 0 & \Delta t\Delta\omega_s & 1-(\beta+1)\Delta t\cdot\omega_{s/2}
\end{bmatrix}
\begin{bmatrix} V_{Ar}^{n} \\ V_{Ai}^{n} \\ V_{Cr}^{n} \\ V_{Ci}^{n} \\ V_{Sr}^{n} \\ V_{Si}^{n} \end{bmatrix}
+
\begin{bmatrix} \Delta t\cdot\omega_{a/2}R_A I_{Br}^n \\ \Delta t\cdot\omega_{a/2}R_A I_{Bi}^n \\ 0 \\ 0 \\ \Delta t\cdot\omega_{s/2}R_s I_{Gr}^n \\ \Delta t\cdot\omega_{s/2}R_s I_{Gi}^n \end{bmatrix}
$$

Beam Loading Term

Cavity Driving Term

Reflection

$$
\begin{cases}
V_{Rr}^{n+1} = \sqrt{\beta}\cdot V_{Sr}^{n} - \dfrac{R_s I_{Gr}^n}{2\sqrt{\beta}} \\
V_{Ri}^{n+1} = \sqrt{\beta}\cdot V_{Si}^{n} - \dfrac{R_s I_{Gi}^n}{2\sqrt{\beta}}
\end{cases}
$$

(1) Time-evolutionary simulation of baseband (I,Q-components) by FPGA in real-time.
(2) Simulation of 3-cavity coupled system (π/2 mode operation).
(3) Direct RF signal (509MHz) input & output.
(4) Cavity reflection signal is simulated in real-time response.
(5) Tuner control (tuning/detuning) can be also simulated with pulse train signal input.
(6) Beam loading effect can be included.
(7) Cavity parameters is variable arbitrarily.
(8) Bench-top use or rack mounting

$\Delta t = \dfrac{1}{f_{clock}}$ $\omega_{\mu/2} = \dfrac{\omega_\mu}{2Q_\mu}$ $\mu : s, c, a$

$\Delta\omega_\mu = \omega_\mu - \omega_{rf}$ **: Detuning** β **:Input Coupling**

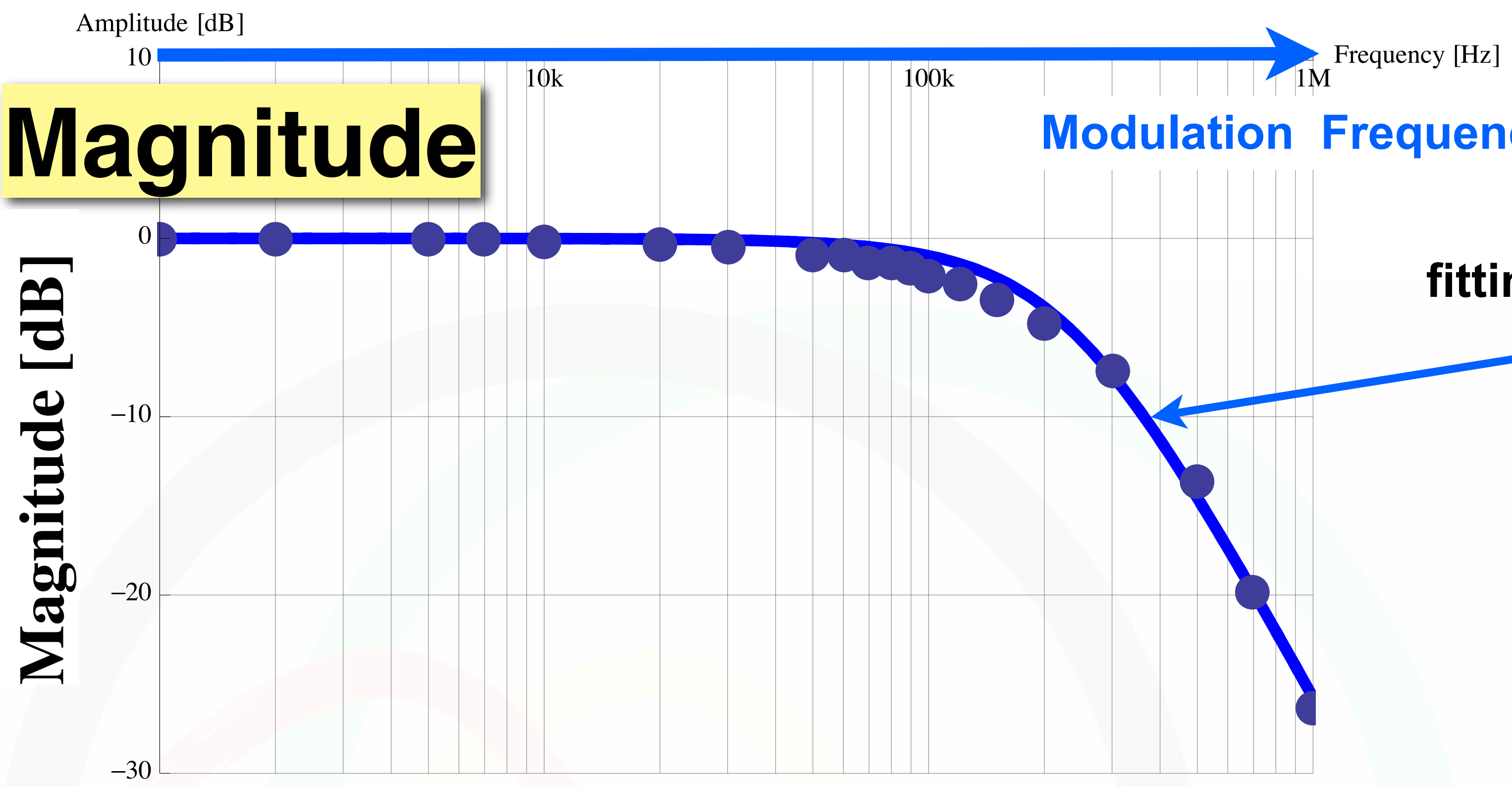
$K_\mu = \dfrac{k_\mu}{2}$: Coupling factor with C-cav.

R_μ : Shunt Impedance

Response Property - **Klystron Bandwidth**

(open loop)

Measured Result



T_d : Delay

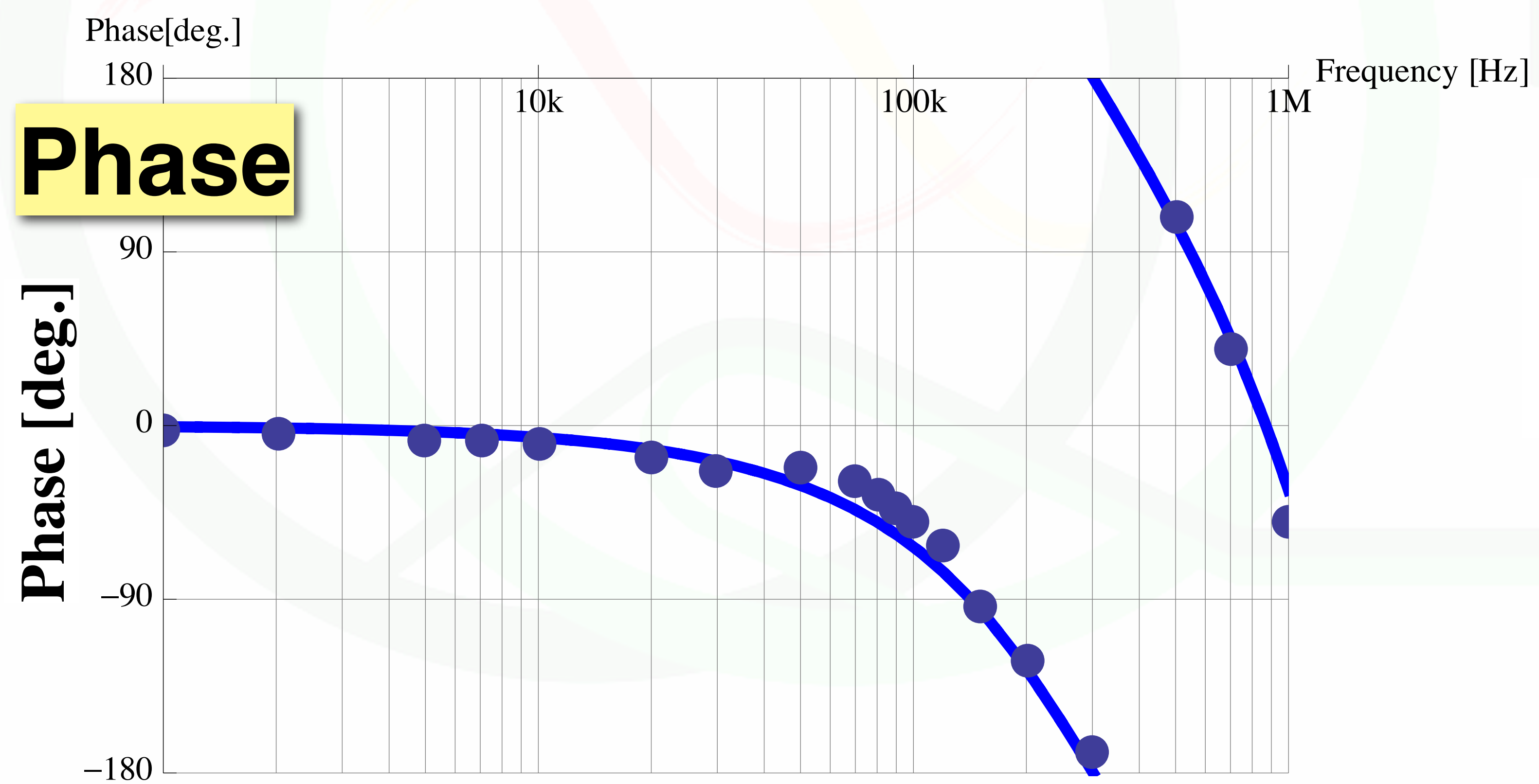
fitting curve with

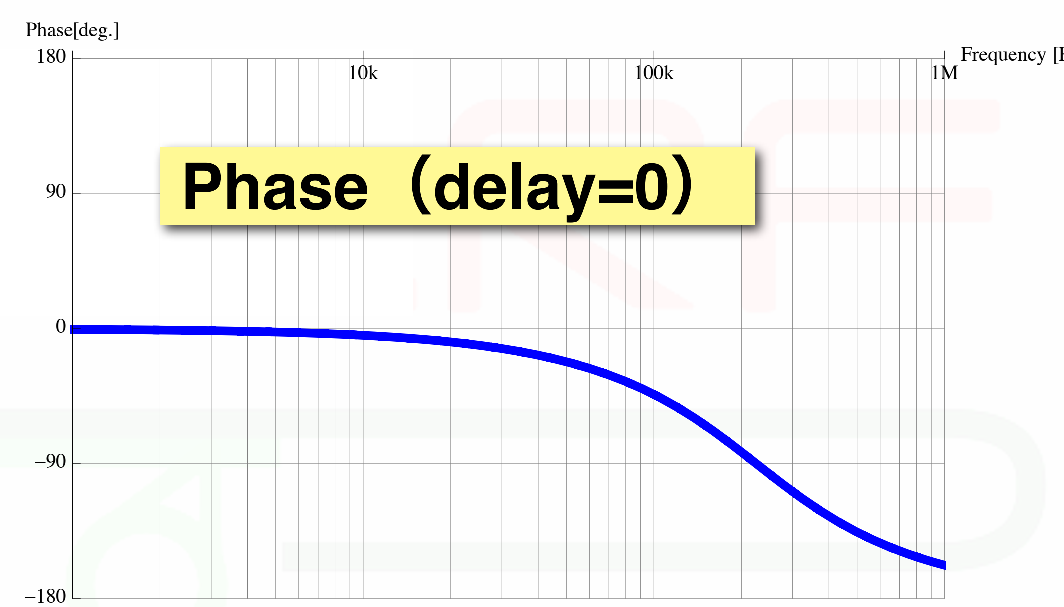
$$H_{kly}[s] = \frac{1}{1 + s/\omega_{kly} + s^2/\alpha} \bullet e^{-s \cdot T_d}$$

ω_{kly}=130 kHz

T_d=650ns

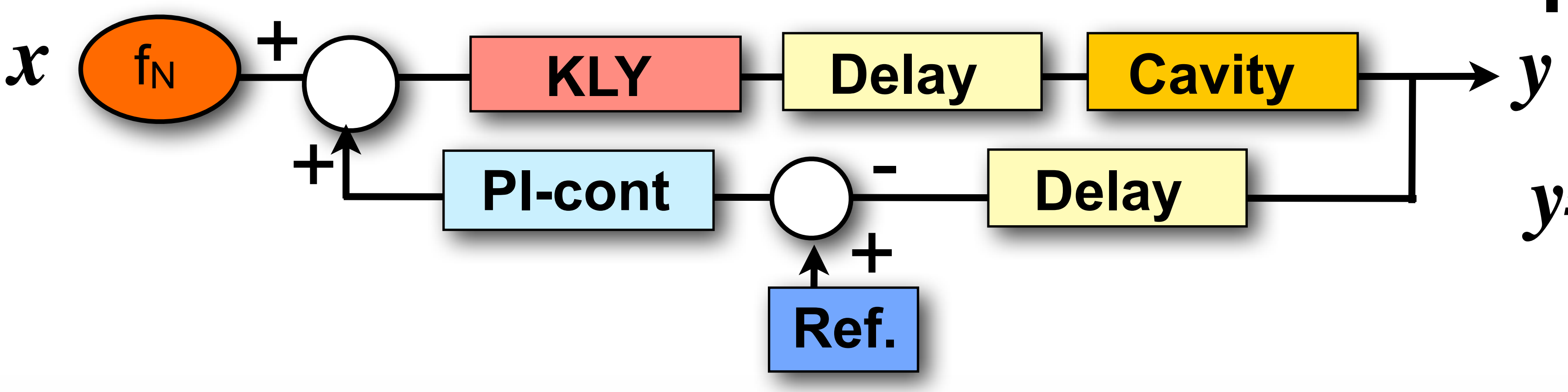
$\alpha=2.1\times10^{12}$





Disturbance Rejection Characteristics

in the closed loop



$y = H[s] \bullet x$

Calculation & Measurement