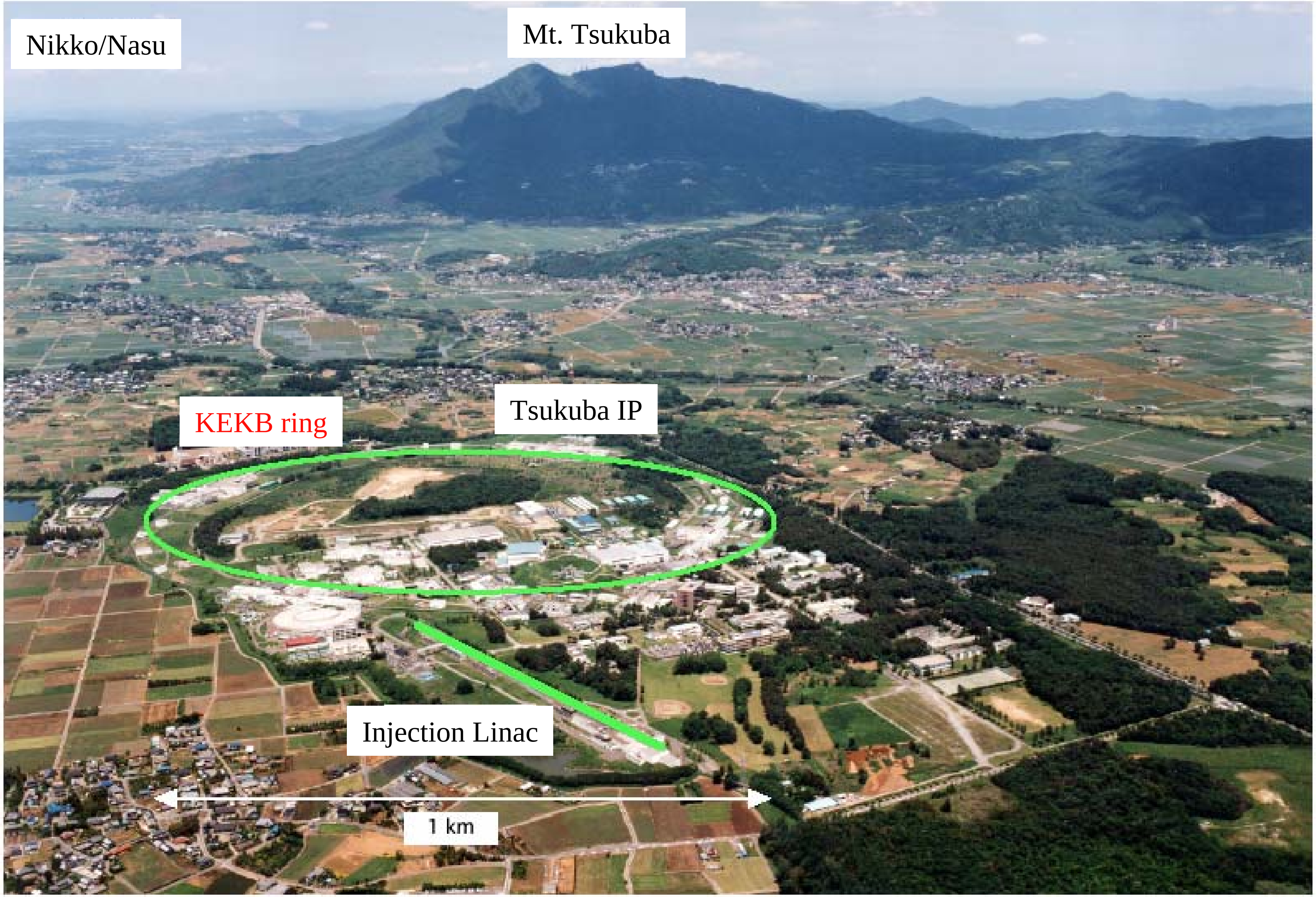
KEKB RF System

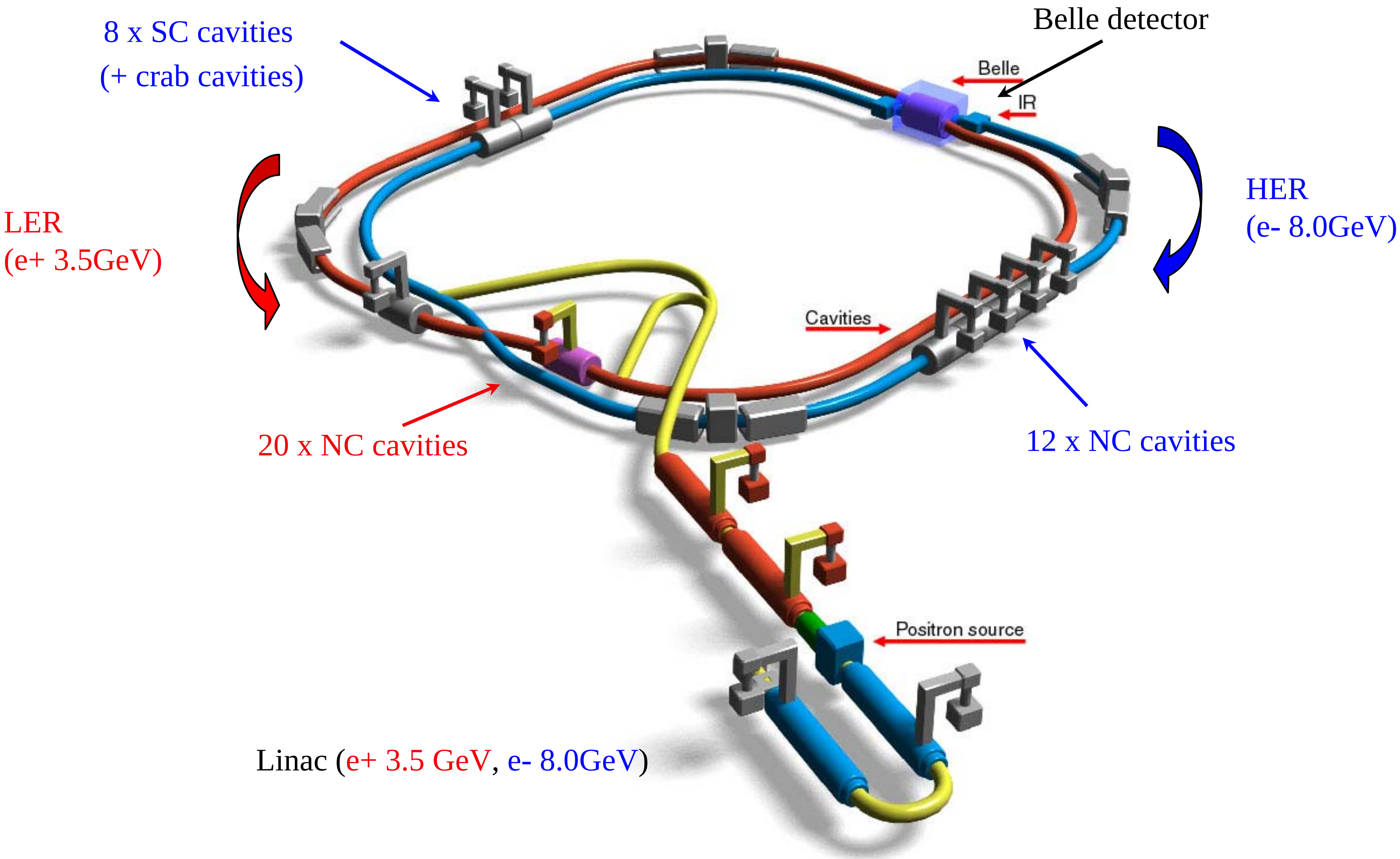
1. *Overview of KEKB-RF*
2. *Operational experience*
3. *Upgrade projects*

K. AKAI for KEKB-RF group

LLRF workshop, Oct. 10, 2005 at CERN


Nikko/Nasu
Mt. Tsukuba
KEKB ring
Tsukuba IP
Injection Linac
1 km

KEKB factory and injector



History of KEKB

- 1994 Construction started
- 1995 Jun. Design report completed
- 1998 Dec. Beam commissioning started
- 1999 May Belle detector installed
- 2001 Apr. Reached record luminosity
- 2003 May Reached design luminosity ($1x10^{34}$ /cm^2s)
- 2005 May Peak luminosity is 1.58 $x10^{34}$ /cm^2s

Number of RF cavities and RF stations

	LER	HER	
	ARES (Kly)	ARES (Kly)	SCC (Kly)
1998 Dec.	12 (6)	6 (3)	4 (4)
1999 Oct.	16 (8)	10 (5)	4 (4)
2000 Oct.	16 (8)	10 (5)	8 (8)
2001 Oct.	20 (10)	12 (6)	8 (8)
2005 Sep.	20 (10)	12 (7)	8 (8)
2006	Crab cavities will be installed.		

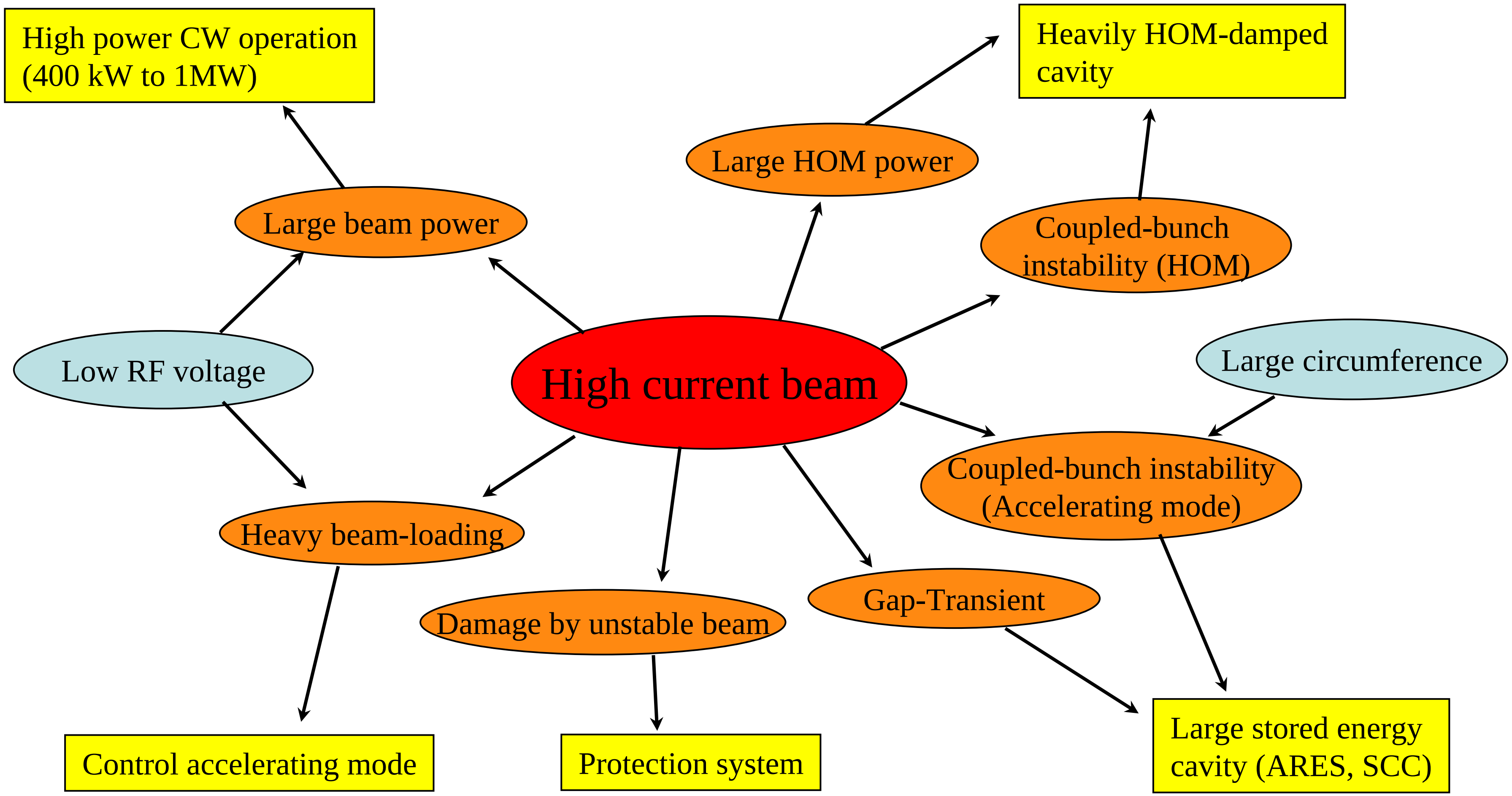
QuickTimeý Ç²
TIFFÅià èkÇ»ÇµÅj êLí£ÉvÉçÉOÉâÉÄ
Ç™Ç±ÇÃÉsÉNÉ`ÉÉÇ¾å©ÇÈÇžÇ½Ç…ÇÕïKóvÇ-Ç ÅB

RF-related parameters (design)

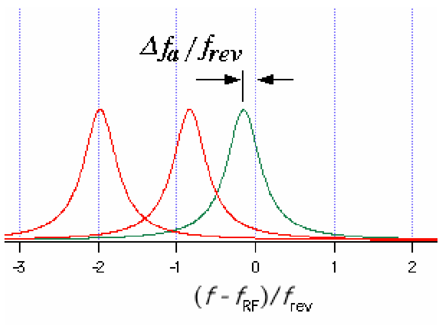
Ring	LER	HER	
Beam energy (GeV)	3.5	8.0	
Beam current (A)	2.6	1.1	
Wiggler magnets	yes	no	
Energy damping time (ms)	23	23	
Energy loss/turn (MeV)	1.6	3.5	
Total beam power (MW)	4.5	4.0	
Total RF voltage (MV)	10	17.9	
Bunch length (mm)	4	4	

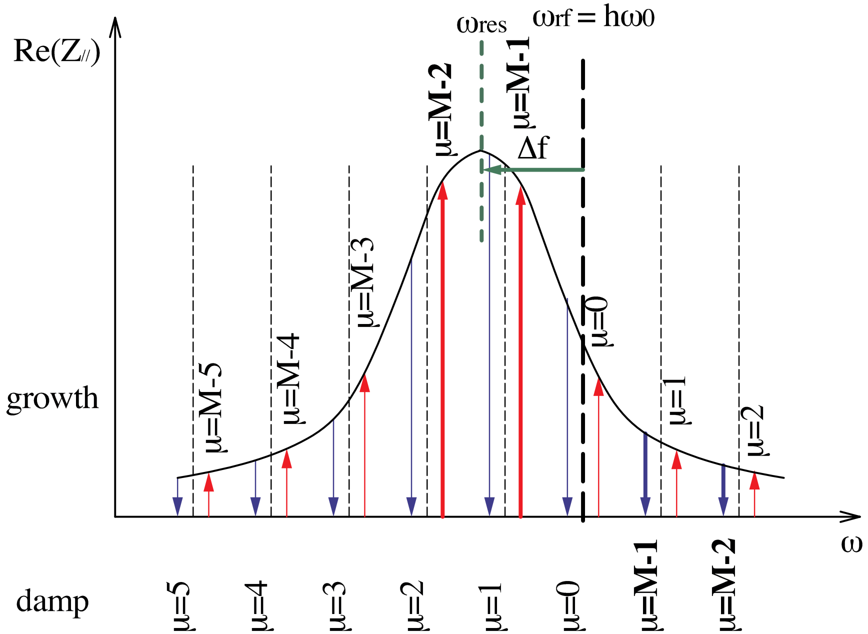
Cavity type	ARES	ARES	SCC
No. of cavities	20	12	8
Voltage /cav. (MV)	0.5	0.5	1.5
Input coupling	2.7	2.7	-
Loaded-Q value (x10E4)	3.0	3.0	7.0
Beam power /cav. (kW)	225	170	240
Wall loss /cav. (kW)	150	150	-
Klystron power (kW)	810	730	270
No. of klystrons	10	6	8

Requirements for KEKB-RF system



CBI due to the accelerating mode





- Detuning in storage rings,
  - Resonant frequency of the accelerating mode should be detuned to match to beam (optimum tuning)

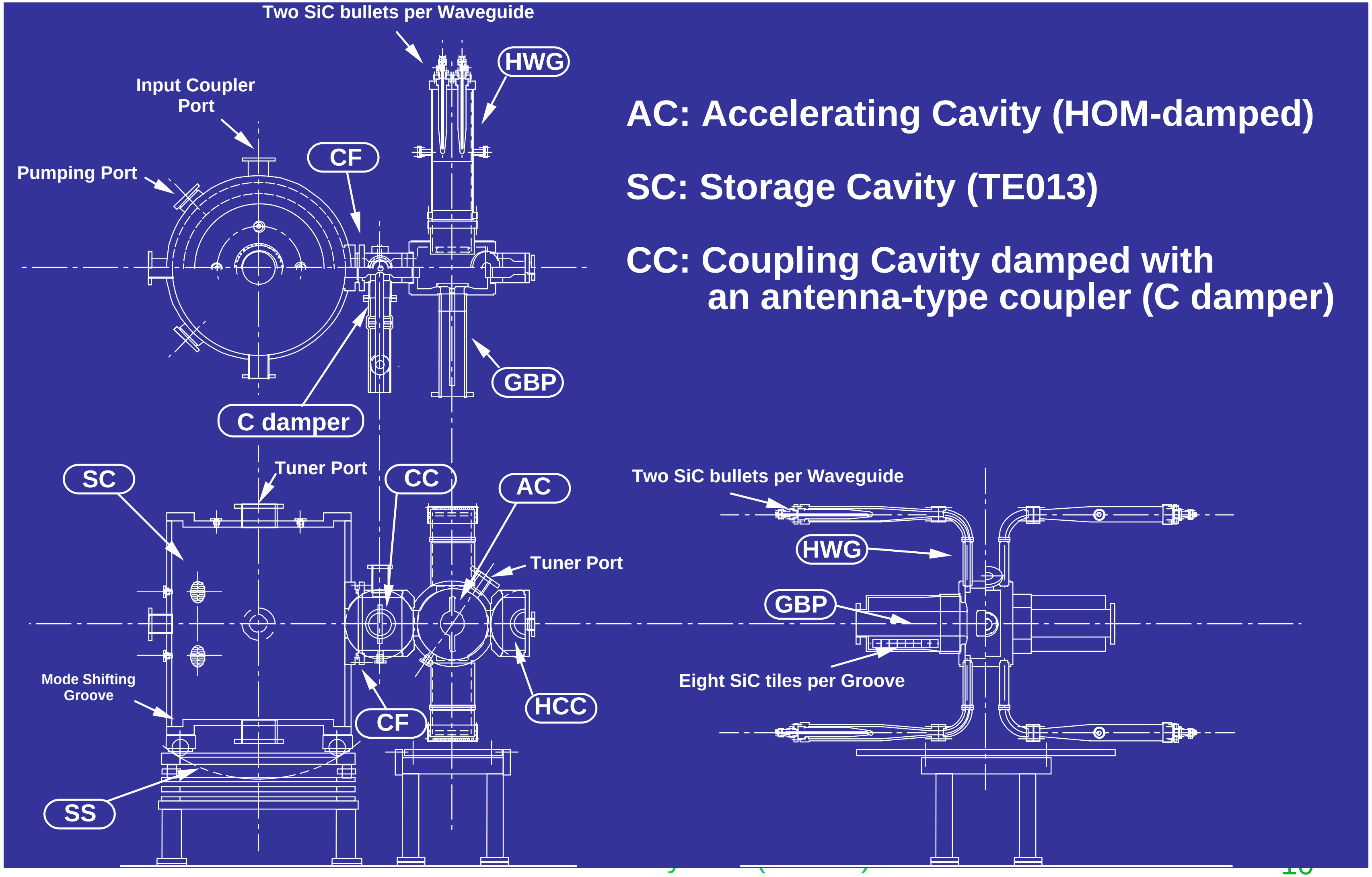
$$\Delta f = -\frac{I_b \sin\phi_s}{2V_c} \times \left(\frac{R}{Q}\right) \times f_{rf} = -\frac{P_b \tan\phi_s}{4\pi U}$$

- In a large circumference ring with high beam current,
  - Large detuning due to high beam current
  - Small revolution frequency
  - High impedance of the accelerating mode
- CBI of -1, -2, etc. modes can arise, growth rate can be very high.
- To reduce the detuning frequency,
  - Operate with high RF voltage
  - High stored energy in cavity
  - Reduce R/Q value of cavity

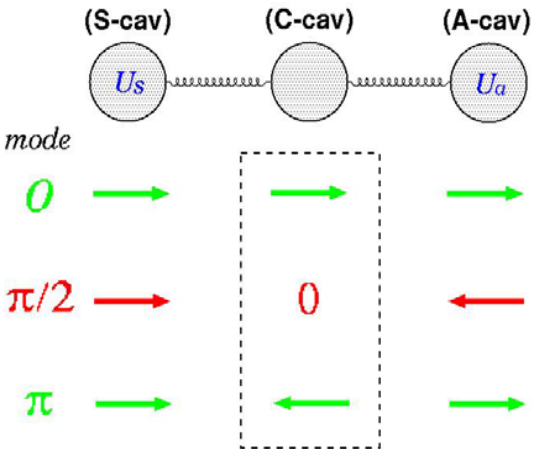
KEKB-RF cavities

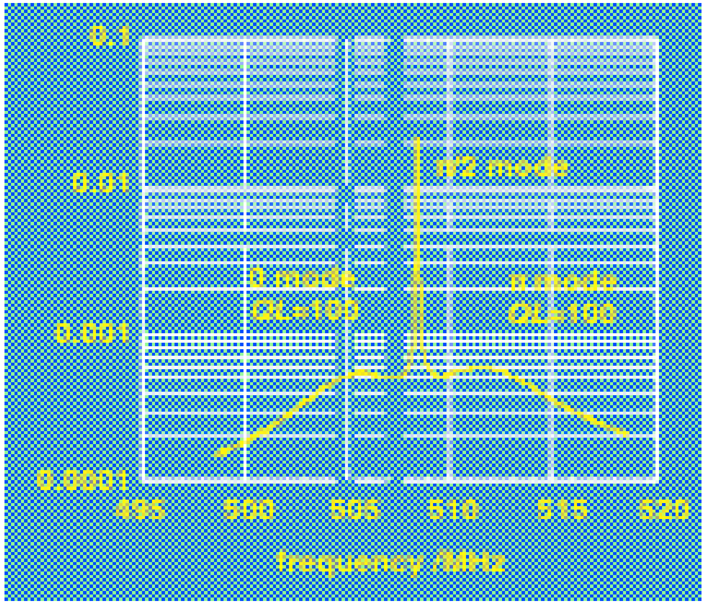
- Large stored energy (ARES, SCC)
  - Suppress the CBI associated with the accelerating mode.
  - Bunch gap transient effect is reduced.
- Heavily-damped structure
  - Suppress the CBI due to HOMs
- Operation
  - LER uses the ARES
    - More suitable for higher beam-loading
  - HER adopts hybrid of SCC and ARES
    - Most of the RF voltage is supplied by the SCC.
    - Phase of ARES is shifted w.r.t. SCC, so that the ARES supplies half of beam power (the other half by SCC).

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



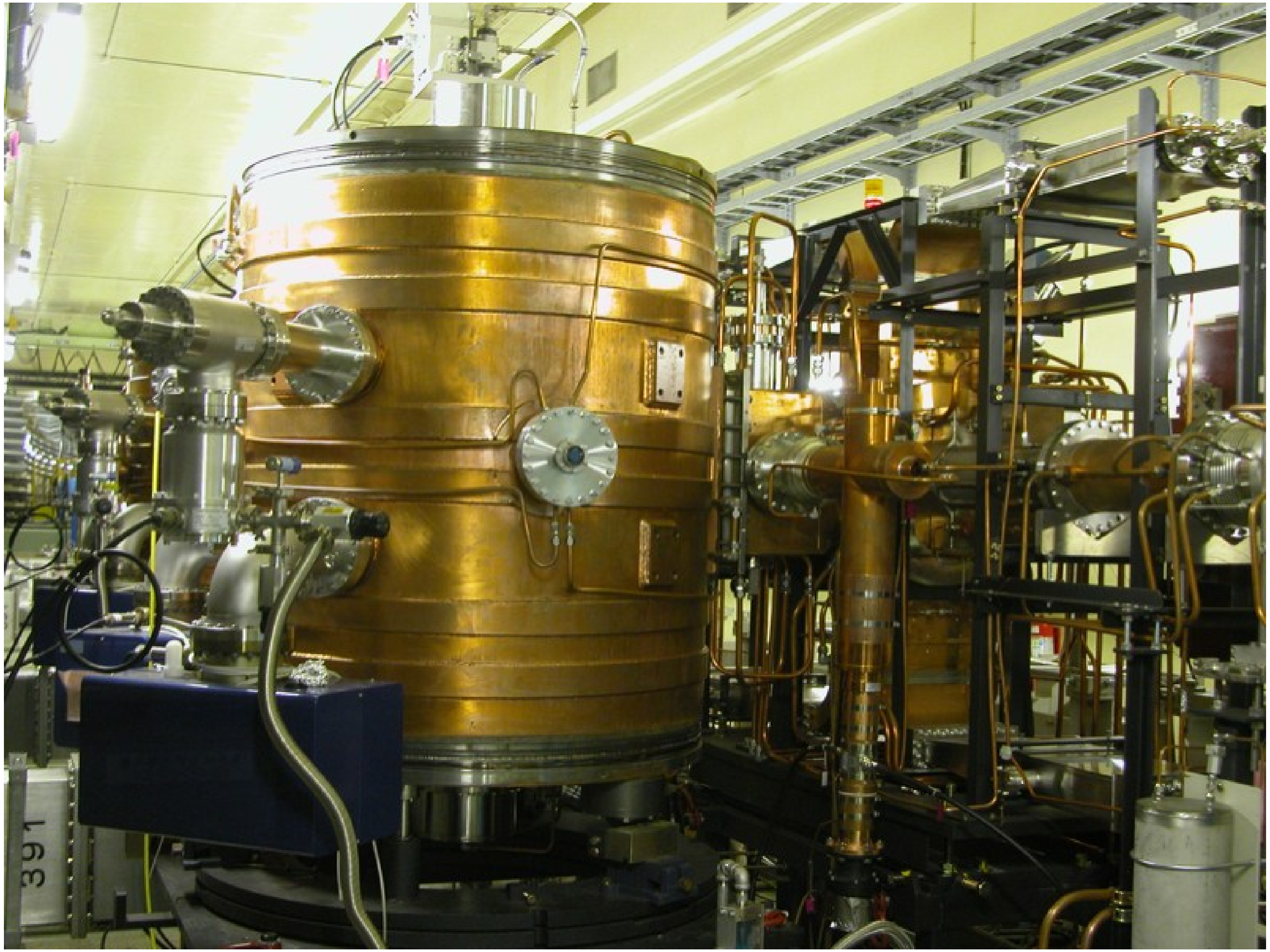
Principle of ARES cavity





- High stored energy in the storage cavity operating at TE013 mode.
- Three modes for the three-cavity system
  - The π/2 mode: operating mode
    - Us:Ua=9:1. Ten times total stored energy compared to the accelerating cavity only. The detuning frequency is reduced to 1/10.
    - The π/2 mode is more stable than other modes against beam-loading or errors.
  - 0 and π modes: parasitic
    - Damped to Q=100 by an antenna at the coupling cavity.
    - The impedance of 0 and π modes is about symmetry w.r.t. the π/2 mode. Growth rate due to these modes are almost cancelled.

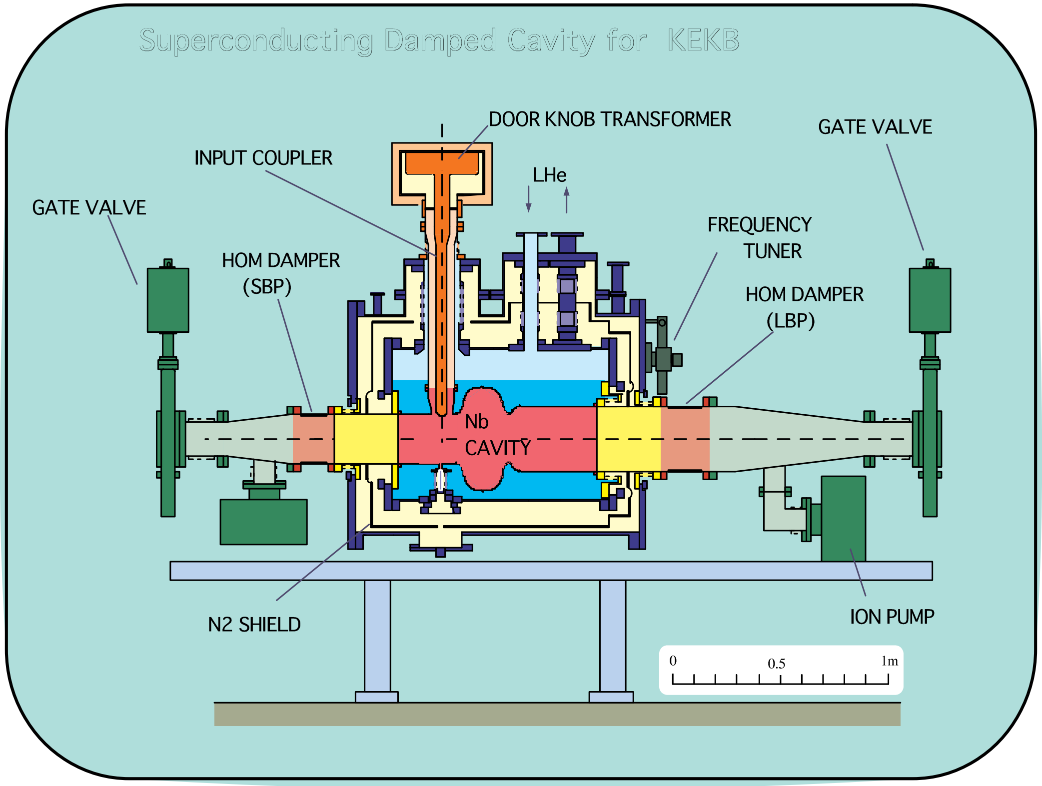
1 set of ARES cavity in KEKB tunnel



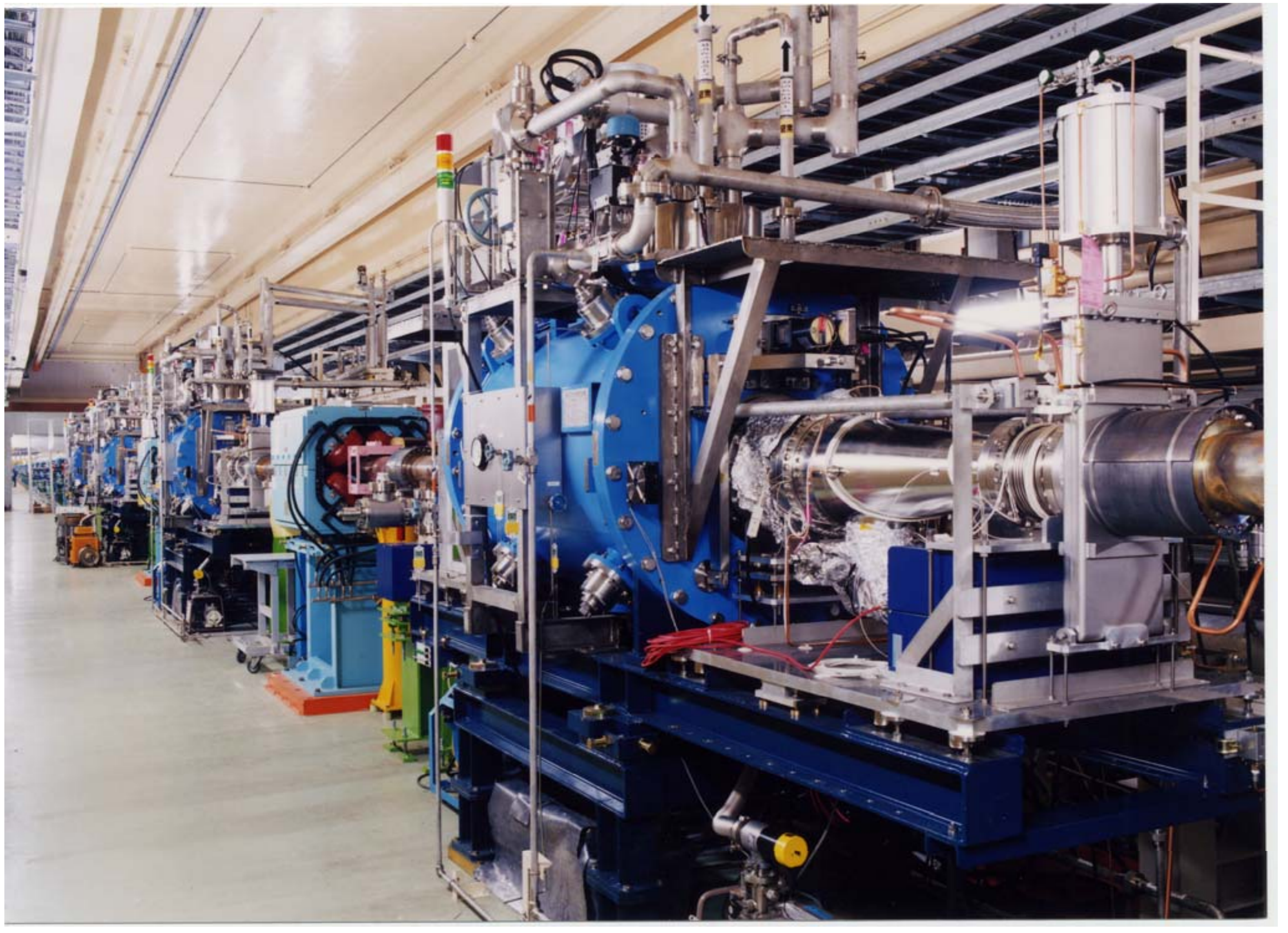
ARES cavities
in Fuji straight section

KEKB superconducting cavity

- Features
  - Single-cell HOM damped cavity.
  - Lower R/Q value and higher voltage than NC cavity: the CBI due to the accelerating mode can be suppressed.
  - Ferrite is attached inside the beam pipe by Hot Isostatic Press method.

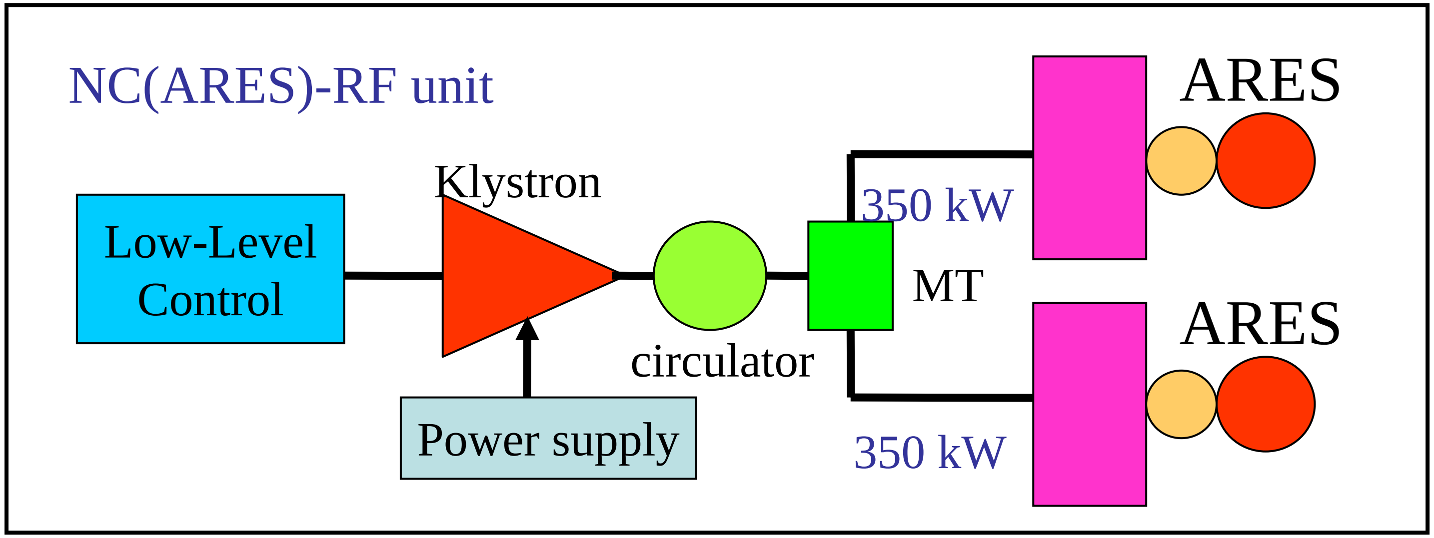


SC cavities in Nikko straight section

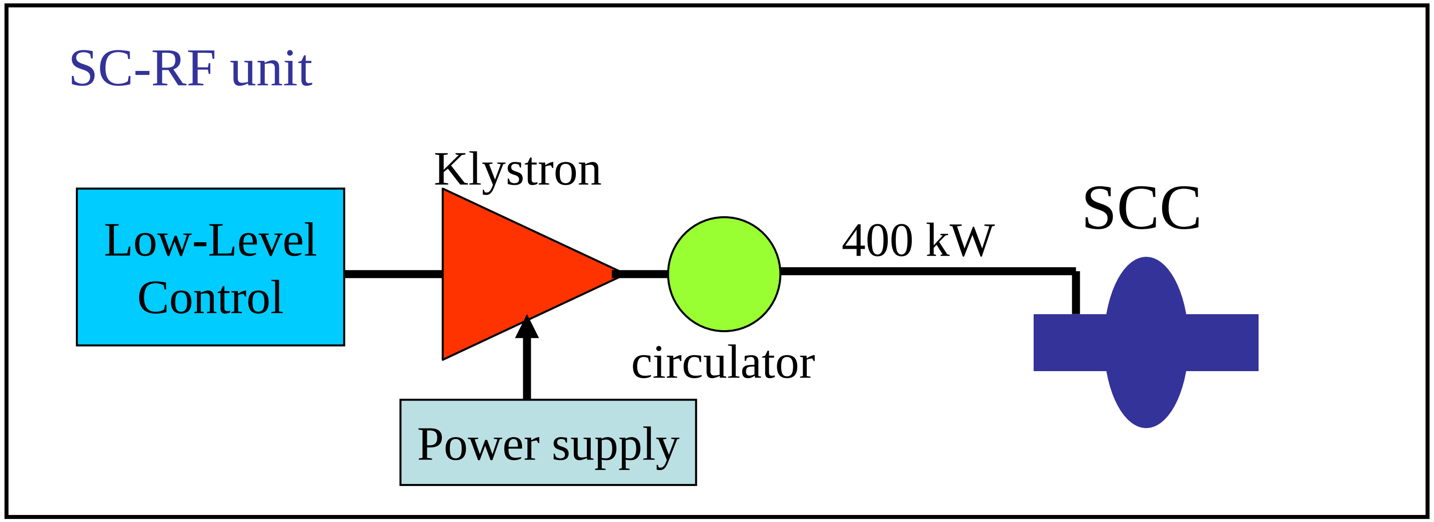


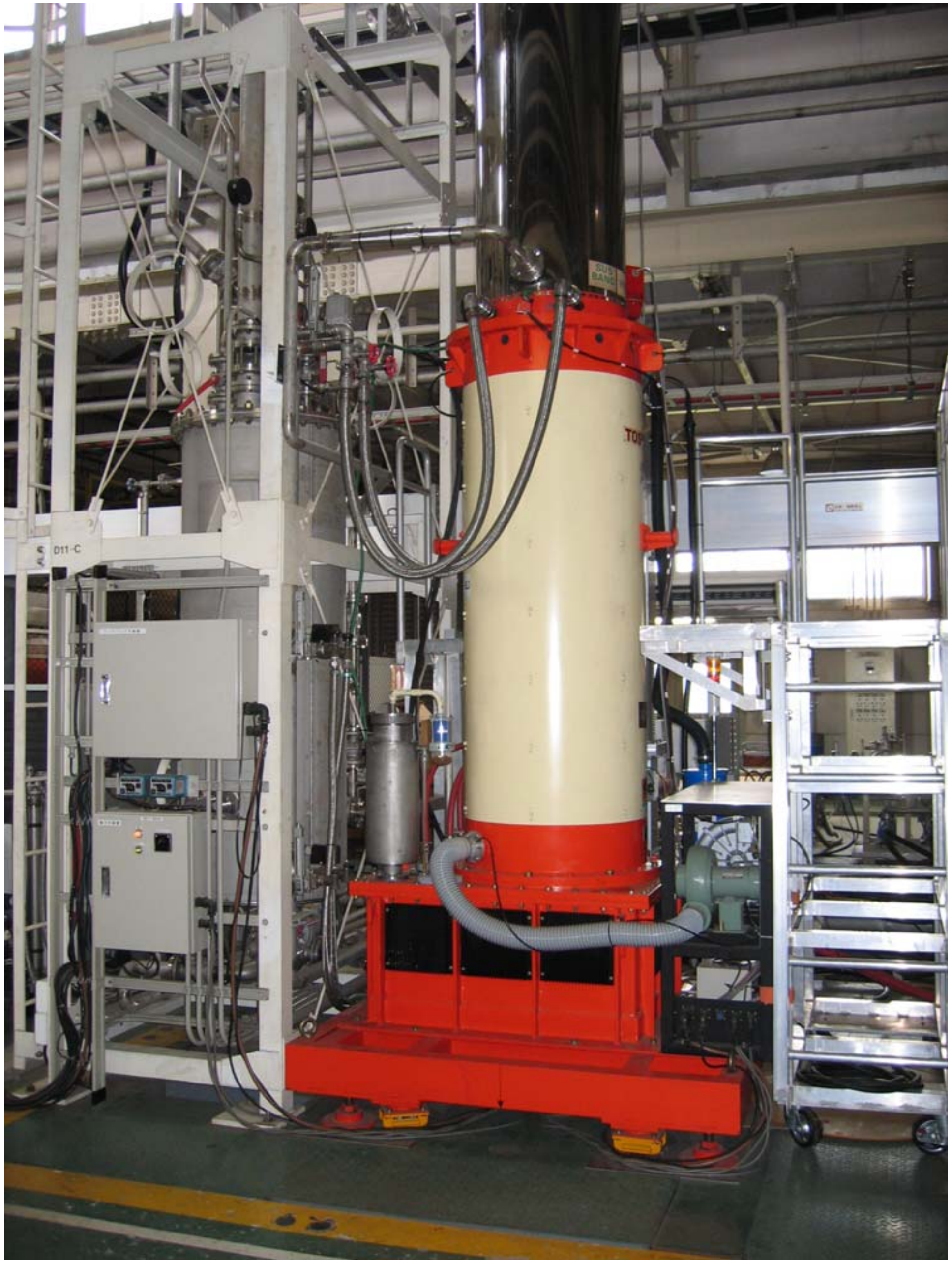
High power and LLRF system

- From TRISTAN to KEKB
  - Same RF frequency (509 MHz).
  - Most of the high-power components such as klystrons, circulators and waveguides were taken from TRISTAN.
  - It reduces construction cost.
  - The RF system and its components have been re-examined to meet the increased demands associated with high luminosity of KEKB.
- As for LLRF
  - Most of control modules also taken from TRISTAN: mostly analog.
  - Incorporated new feedback loops including direct RFFB.
  - Zero-mode and the -1 mode stabilizer was added.
  - Interlock and beam abort trigger system has been improved.



(This year two ARES cavities have been changed to 1:1 configuration.)

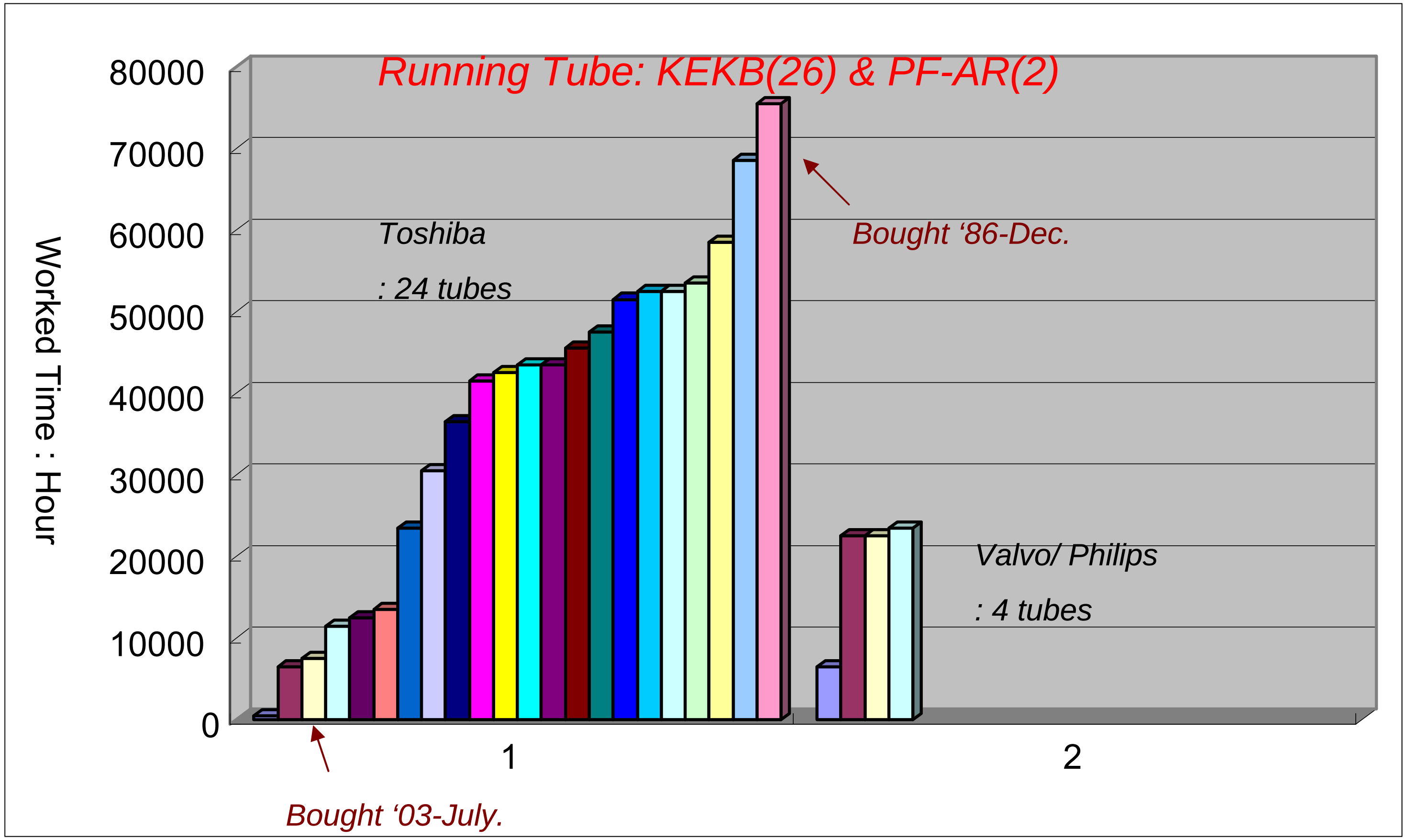




Toshiba 1.2 MW CW Klystron

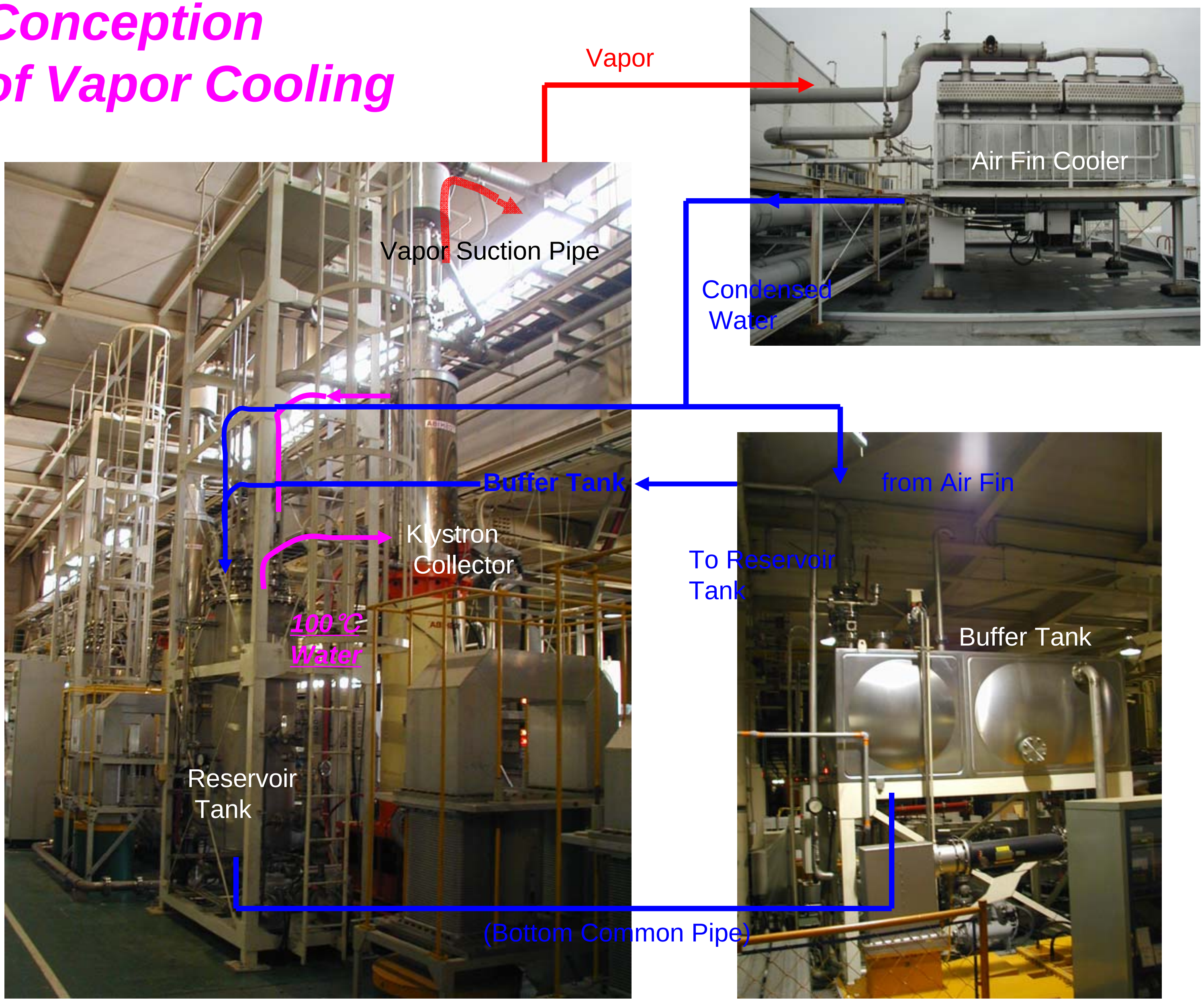
Klystron worked time

: (S. Isagawa; 04/08/16)

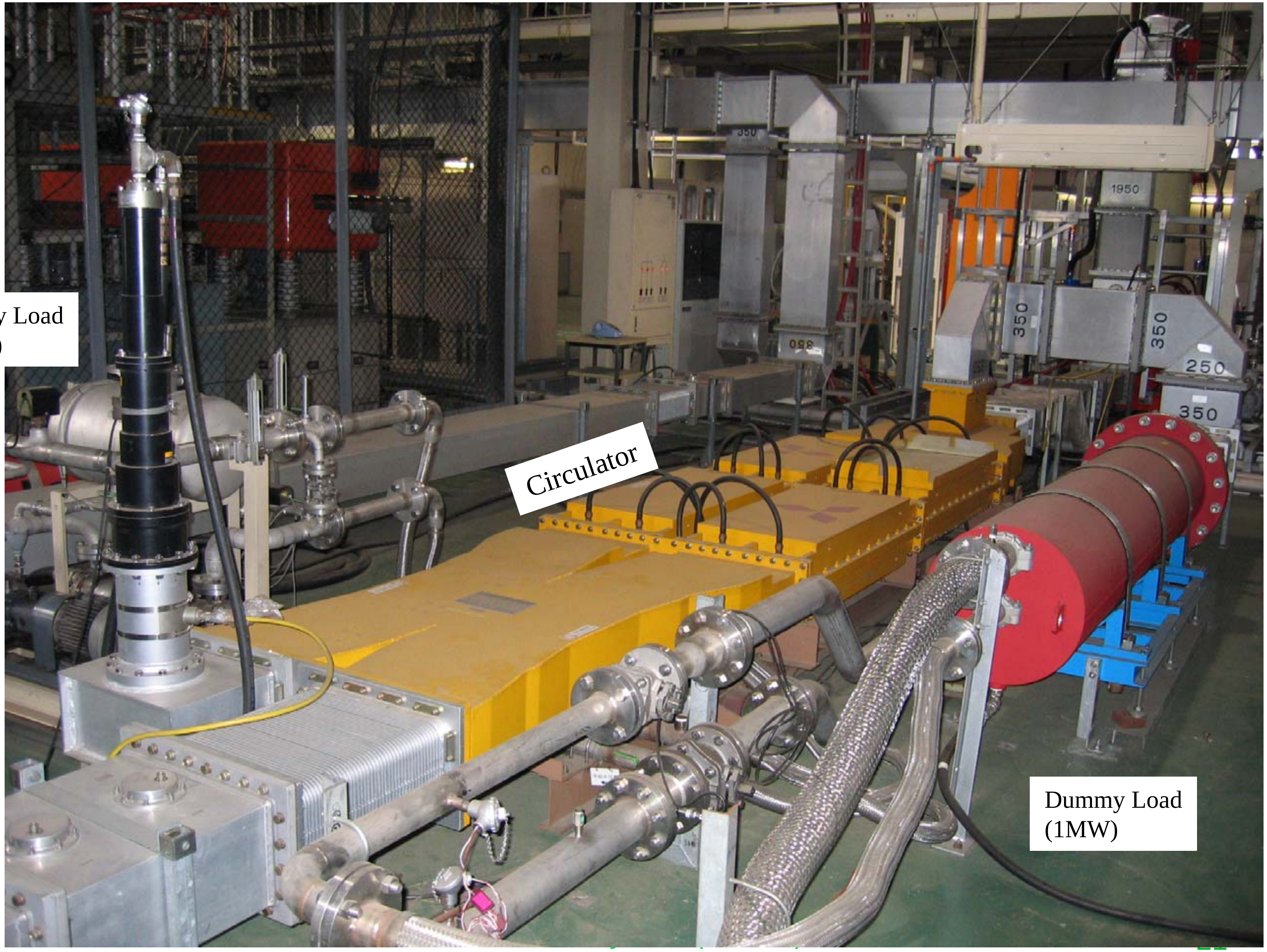


Reliable operation of Klystrons continued since TRISTAN.

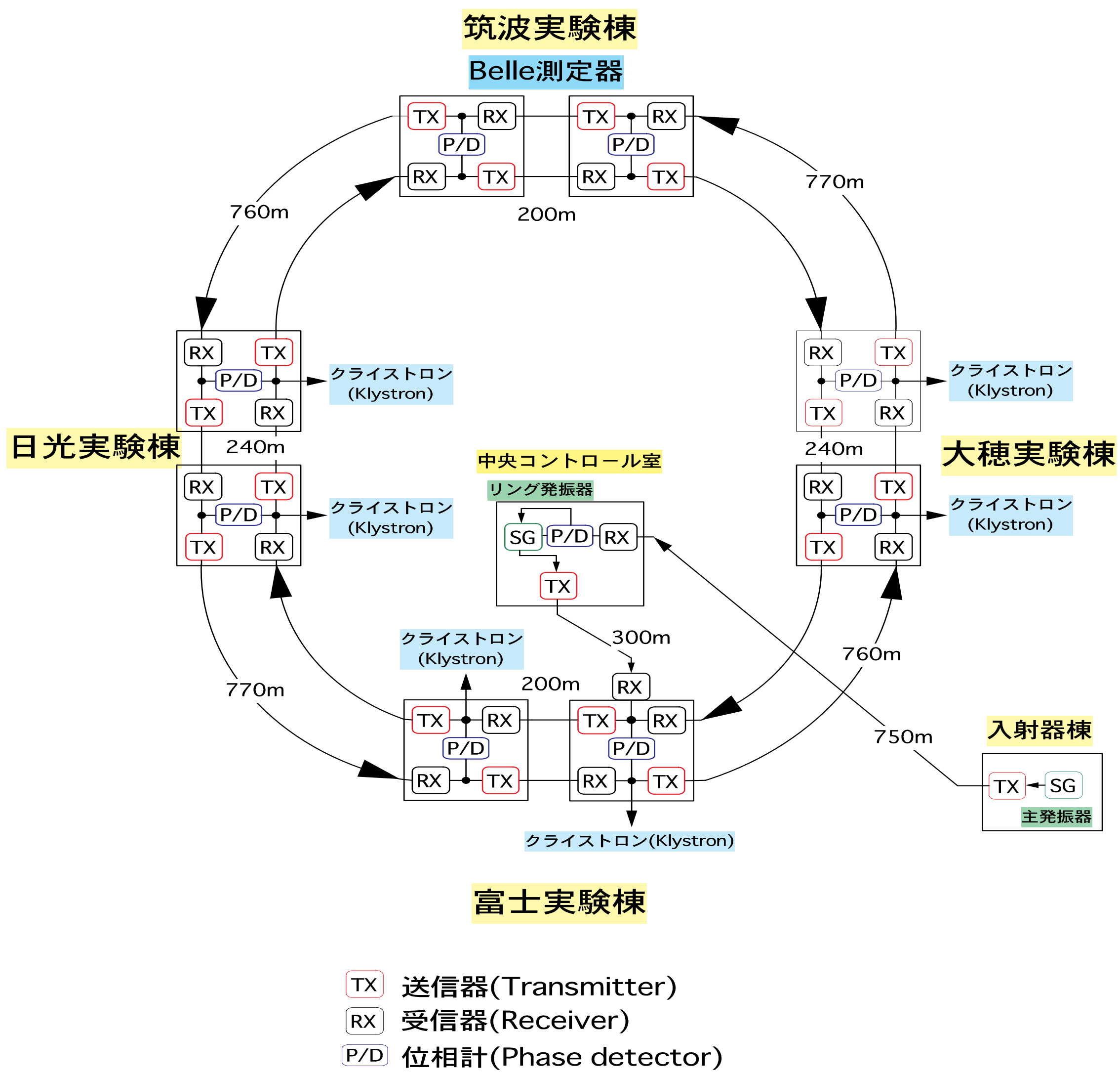
Conception of Vapor Cooling



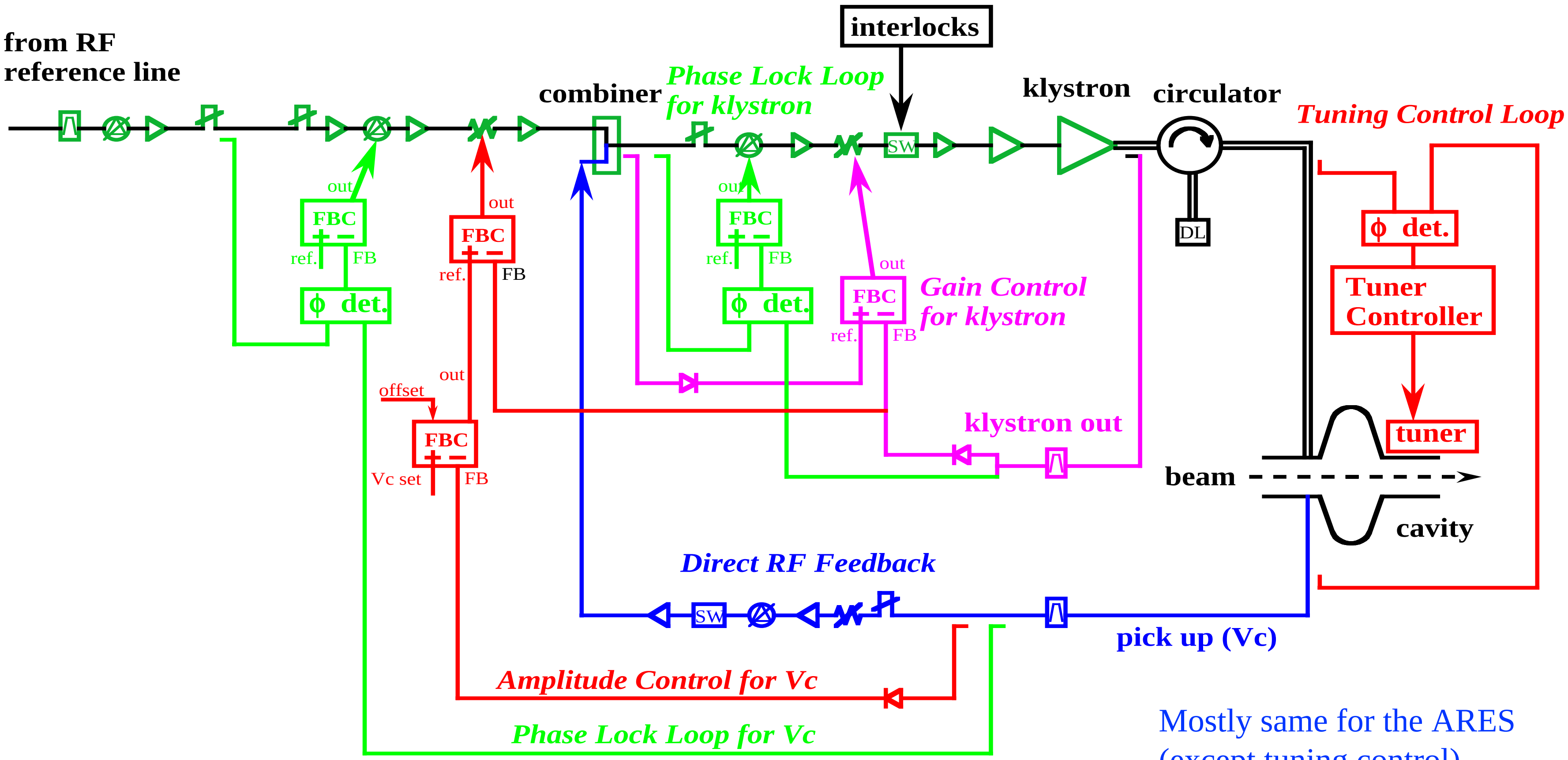
High power RF system (Circulator, Waveguide, Dummy-load)



RF reference line for KEKB ring

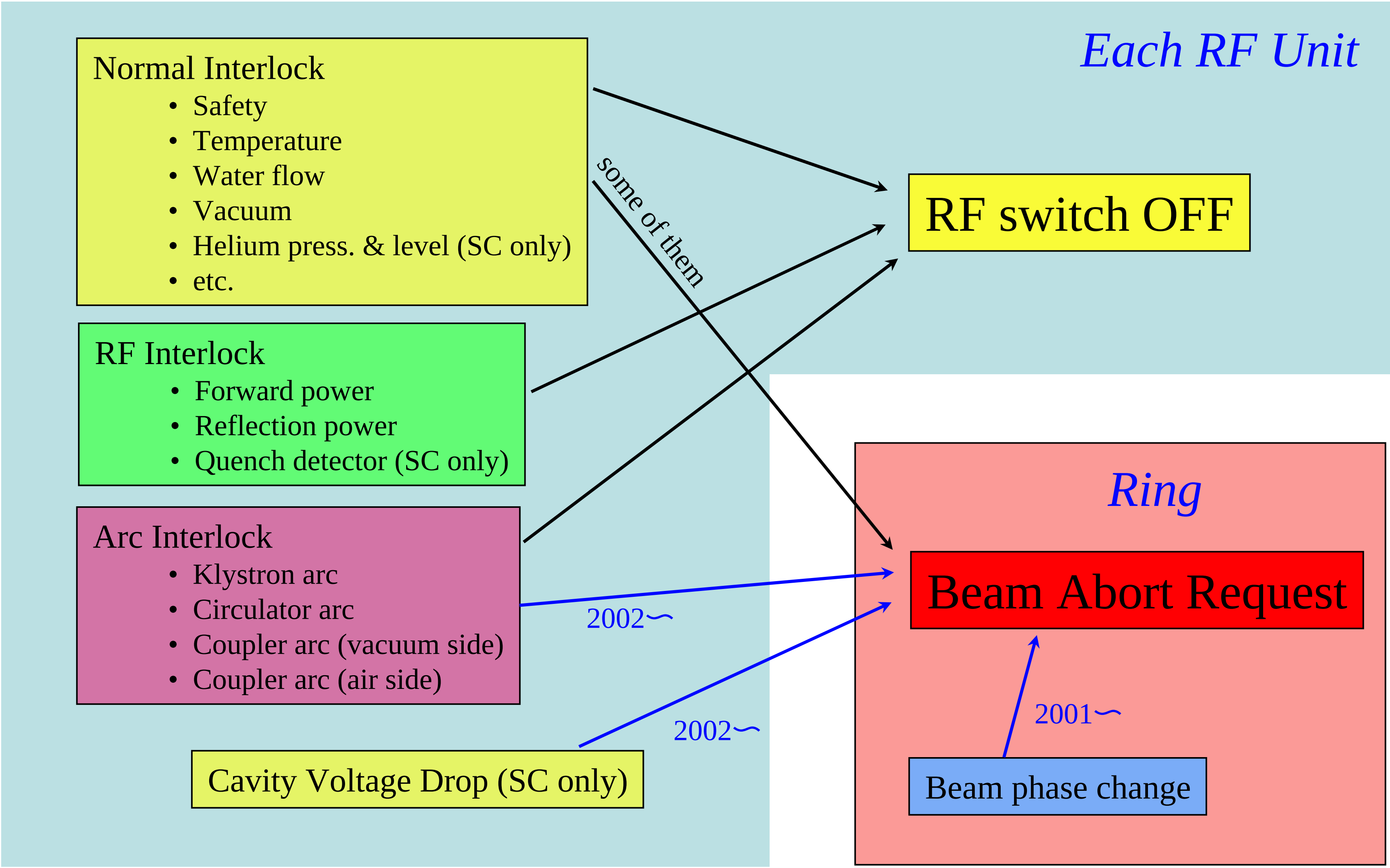


Low-level RF for KEKB Superconducting cavity

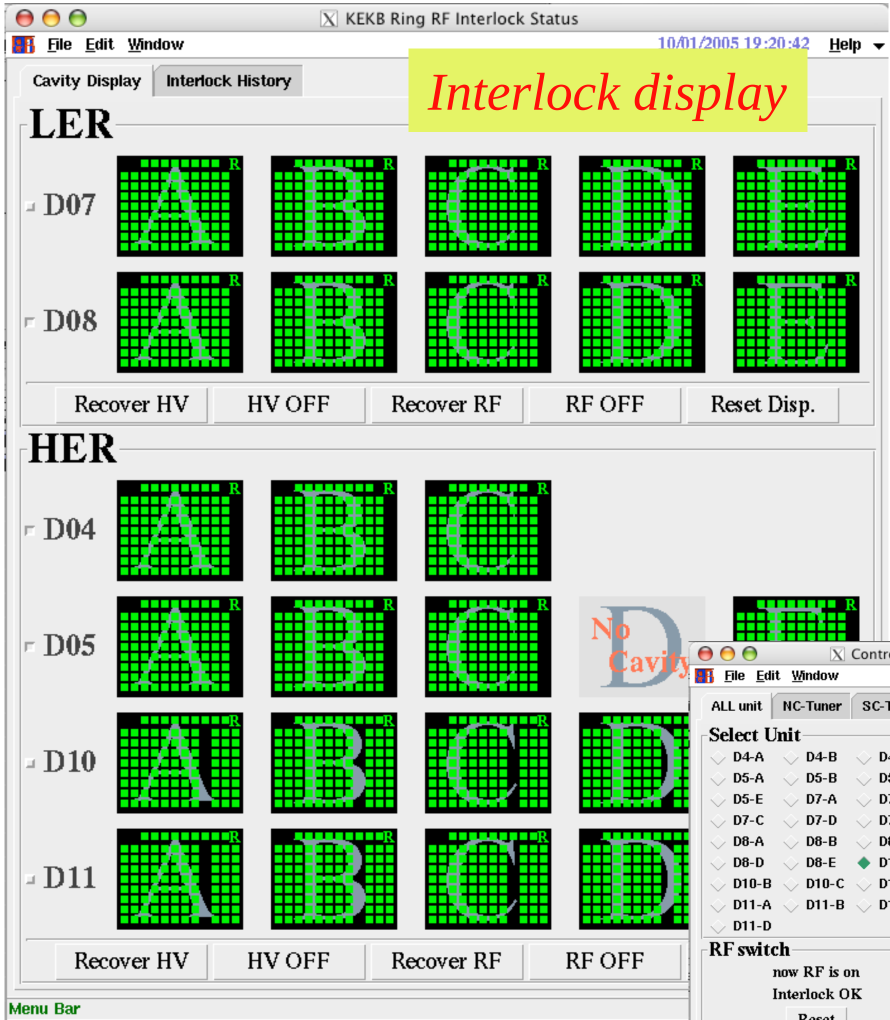


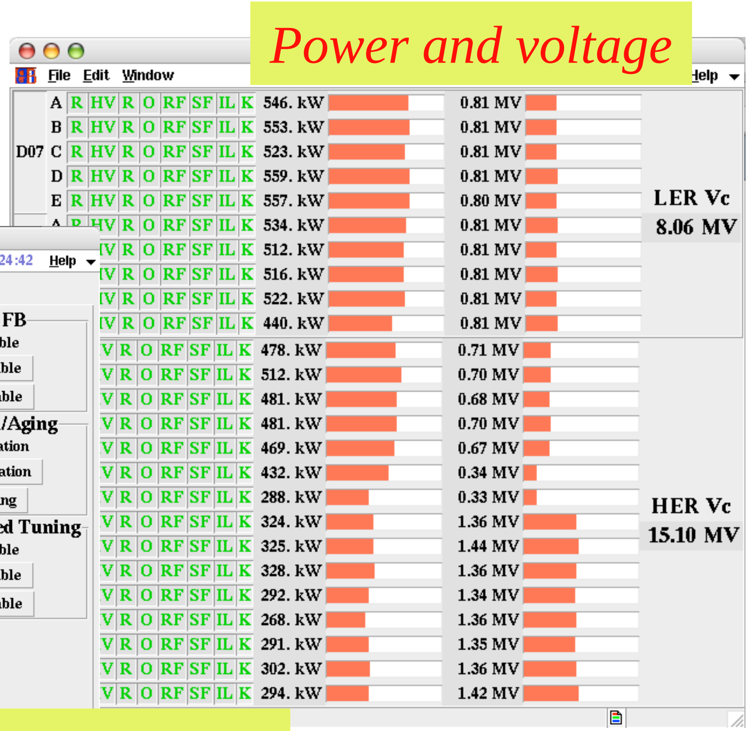
Mostly same for the ARES
(except tuning control).

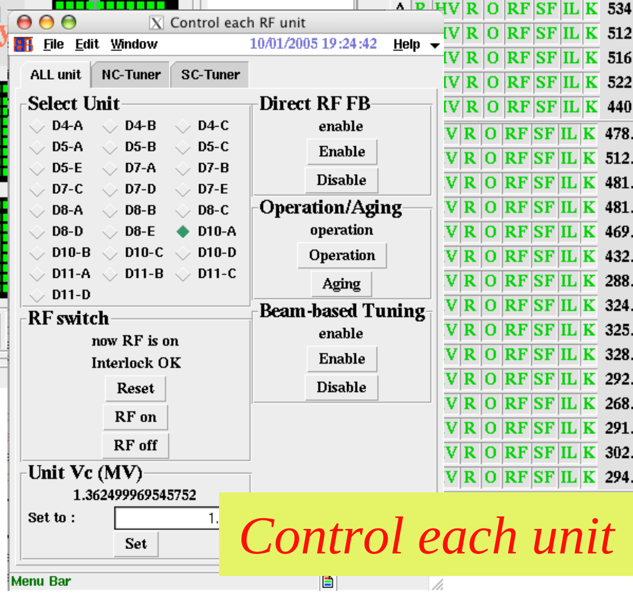
Interlock system



- Control software (EPICS/SAD)
  - Status display
  - Set operating parameters
  - Control each components
  - Recover RF after beam aborts
  - Cavity conditioning
  - etc.







And more・・・

Operational status

- Stable operation continues at high beam current and high RF power.
  - Frequency of beam aborts due to any RF trip is only about 1/day.
- No coupled-bunch instability due to HOMs has been observed.
  - Excellent HOM damping scheme and reliable HOM damper.
- Hardware troubles
  - We had experienced several hardware troubles in the early period.
  - After 2002 we seldom have serious troubles that stop the beam operation for long time.
- Stability of the accelerating mode
  - Most of difficulties due to heavy beam-loading are eased by high stored energy of the ARES and SCC.
  - However, the 0-mode and -1 mode beam oscillation was stronger than expected. They are stabilized by corresponding dampers.

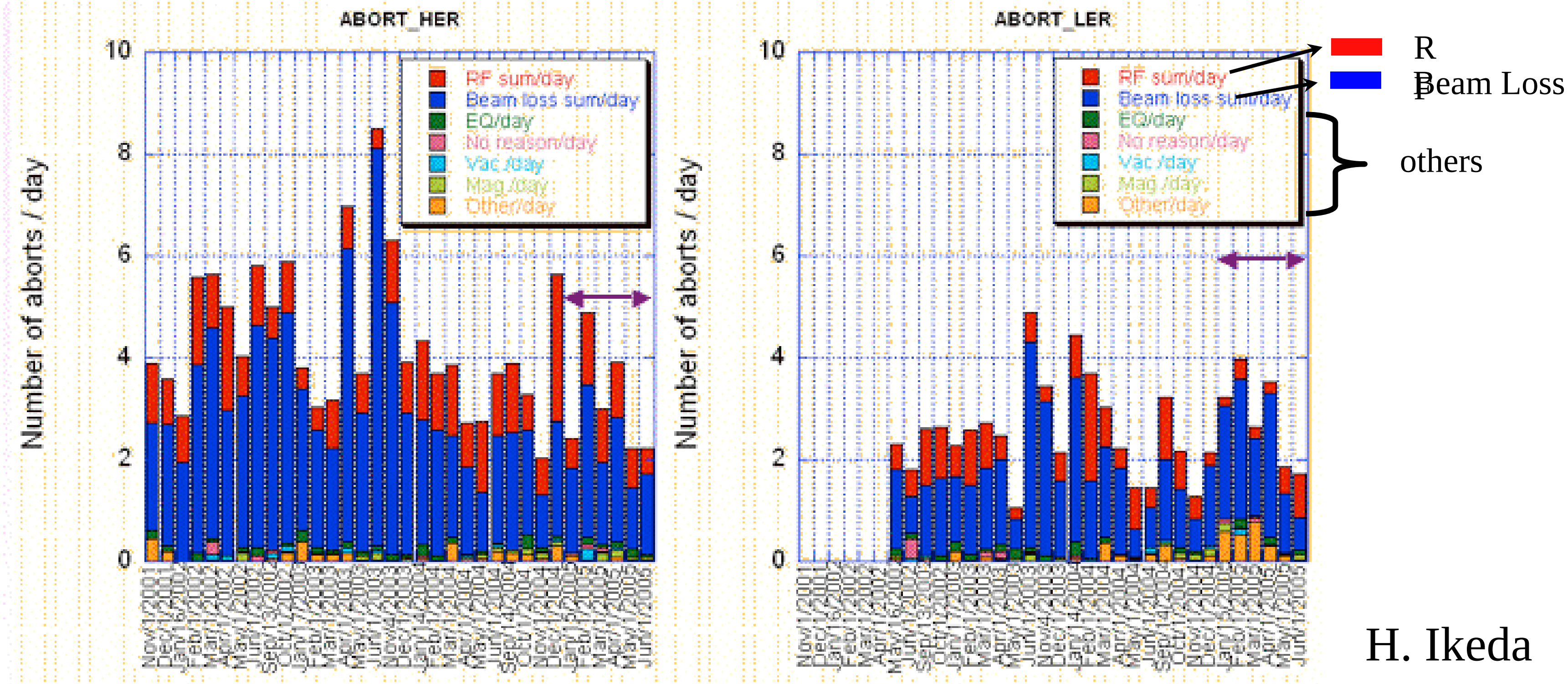
Design and achieved parameters

	LER	HER	
	ARES	ARES	SCC
Max. beam current (mA)	1860 (2600)	1340** (1100)	
Operating RF voltage (MV)	8 (5 ~ 10)	15 (10 ~ 18)	
RF voltage/cavity(MV): Operating Conditioned up to	 0.4 0.55 (0.5)	 0.34 0.475 (0.5)	 1.36 >2.2 (1.5)
Total beam power (MW)	3.3 (4.5)	4.8 (4.0)	
Max. beam power/cavity (kW)	170 (225)	200 (170)	400** (250)
HOM power/cavity (kW)	6		13 (5)

( ) : design values

** record of SC cavities

Beam aborts (2001-2005, monthly)

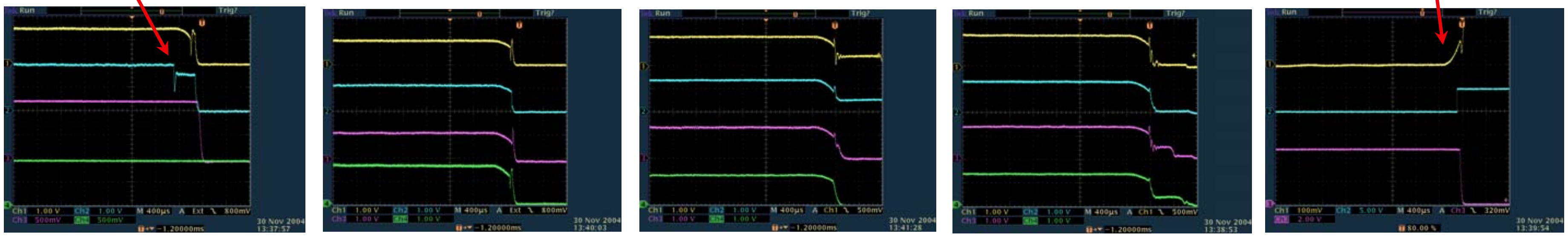


H. Ikeda

- We try to understand the cause of any beam abort.
- Statistics of frequency of beam aborts is routinely taken as above.
- Caused by beam loss (70%), RF (20%), others (<10%).
- Number of aborts in two rings caused by any RF reasons is about 1/day.

RF Abort monitor

RF D04_1(ext. trig.)	RF D05_1(ext. trig.)	RF D10_1 (D10-A trig.)	RF D11_2 (D11-A trig.)	RF D11_1
D04-B cavity voltage D04-C cavity voltage HER DCCT LER DCCT	D05-A cavity voltage D05-B cavity voltage D05-C cavity voltage D04-A cavity voltage	D10-A Cavity voltage D10-B Cavity voltage D10-C Cavity voltage D10-D Cavity voltage	D11-A Cavity voltage D11-B Cavity voltage D11-C Cavity voltage D11-D Cavity voltage	HER Beam Phase HER BPA Req. HER Current (trig.) empty



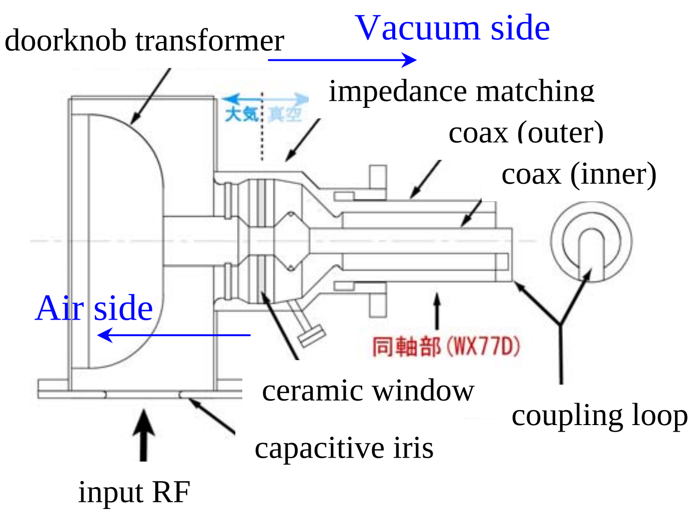
- Transient behavior of every RF station is monitored using oscilloscopes.
- Every beam abort triggers the oscilloscope and the data is automatically logged and displayed on the web so that the operator can judge the cause of abort: RF trips or other reasons? if RF trip, which unit?

Lessons we learned in operation

- Arc sensor for input couplers
- Bad effects of beam aborts due to RF trips
- Zero mode and -1 mode oscillation

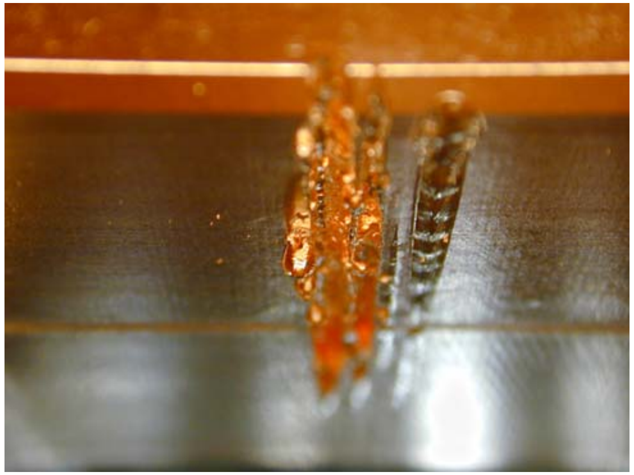
Arc sensor for ARES input coupler

- Before 2000
  - An arc sensor was attached only on the vacuum side of ceramic window.
- Troubles
  - Doorknob transformer burned (Jan. 2000).
  - Ceramic window leaked due to discharge on the air side of the window (Nov. 2000).
  - Ceramic window leaked by circulating beam despite that the arc sensor switched off the RF (Oct. 2001).
- Measures taken
  - An arc sensor is added on the air side of the window.
  - Beam abort is triggered whenever any arc sensor works.
  - Since then no serious accident occurred at the input couplers.



Bad effects of RF trips

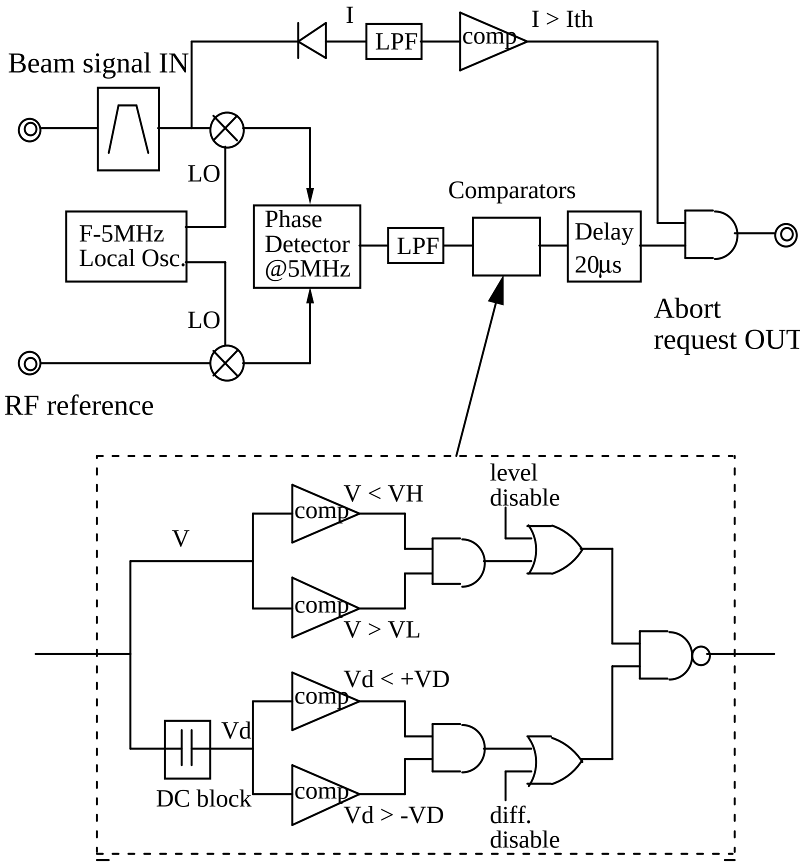
- Unstable beam due to RF trip caused troubles (2001).
  - A large amount of radiation hit the Belle detector. (5 krad/shot worst case!)
  - Movable masks are damaged. Beam life is deteriorated.

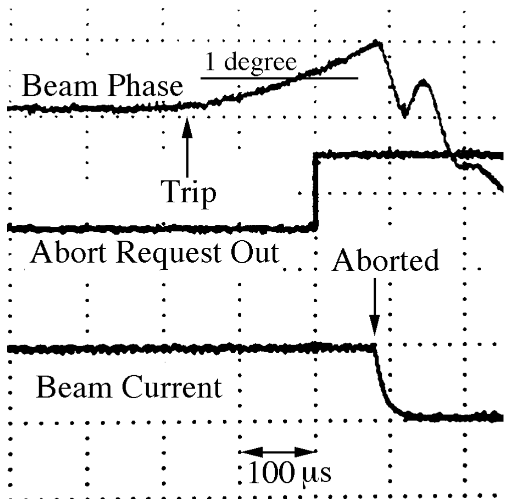


- Abort triggered by interlock system did not help all cases:
  - Some interlocks are not very fast.
  - RF field can become abnormal prior to any interlock work.
- Measures taken (2001〜02):
  - Beam Phase Abort
  - Additional abort trigger by voltage drop and arc sensor
  - PIN diodes
  - Mask head changed from Cu to Ti.
- After 2002, no such bad effects was observed due to RF trips
  - Only one exception: misoperation of master oscillator could not be helped (phase change so fast).

Beam Phase Abort

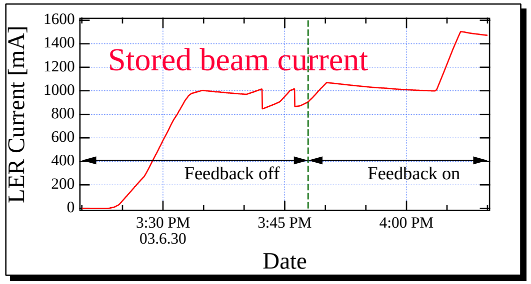
- Relative phase between beam and reference RF is measured.
- Beam phase shift by 1 degree makes a trigger signal to the abort system.

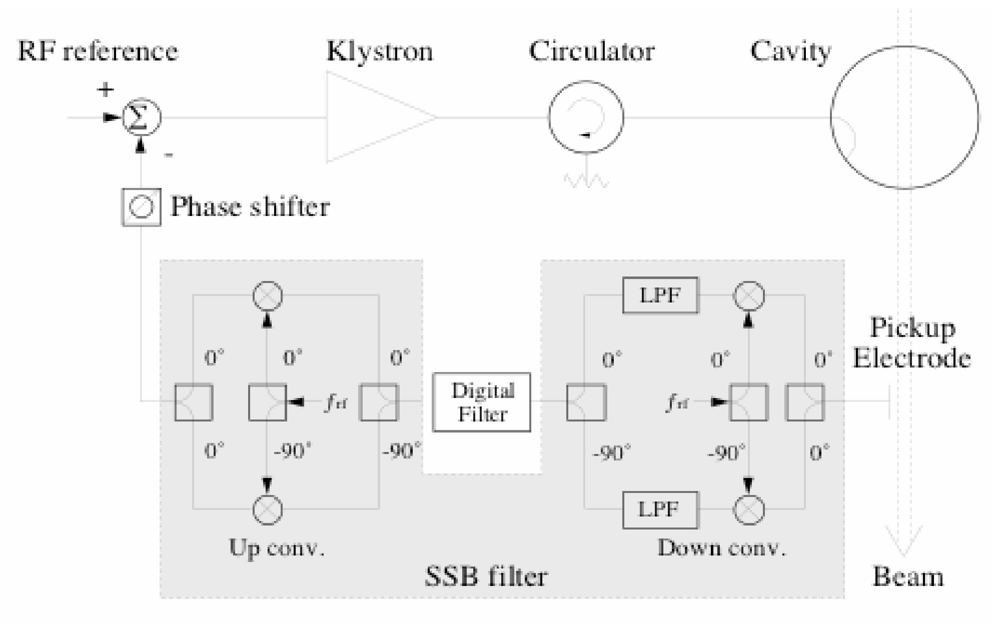


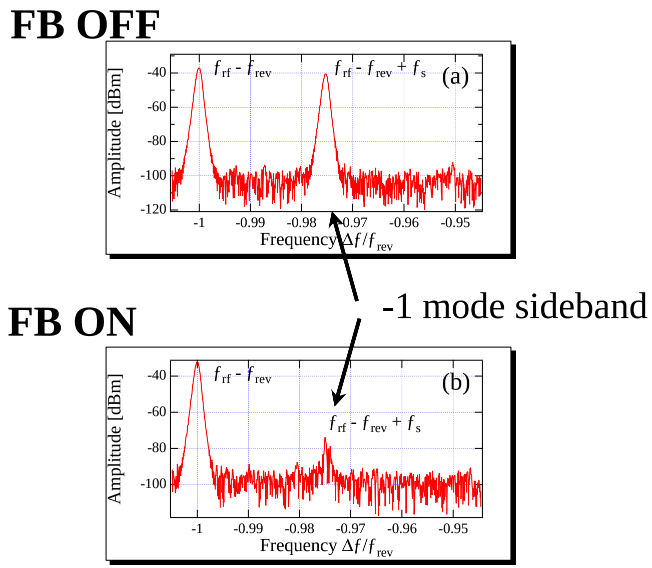


The -1 mode feedback

- 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.

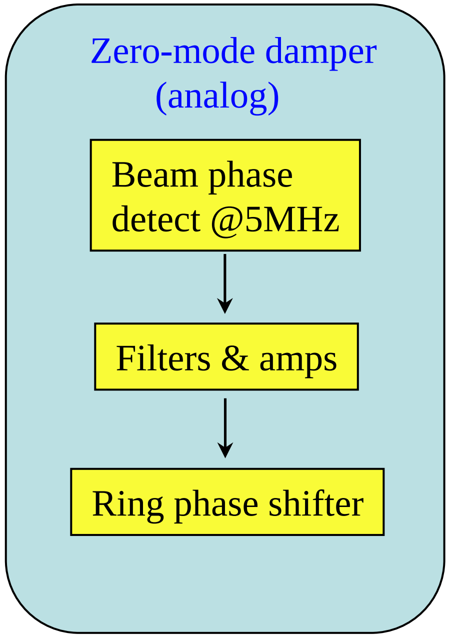


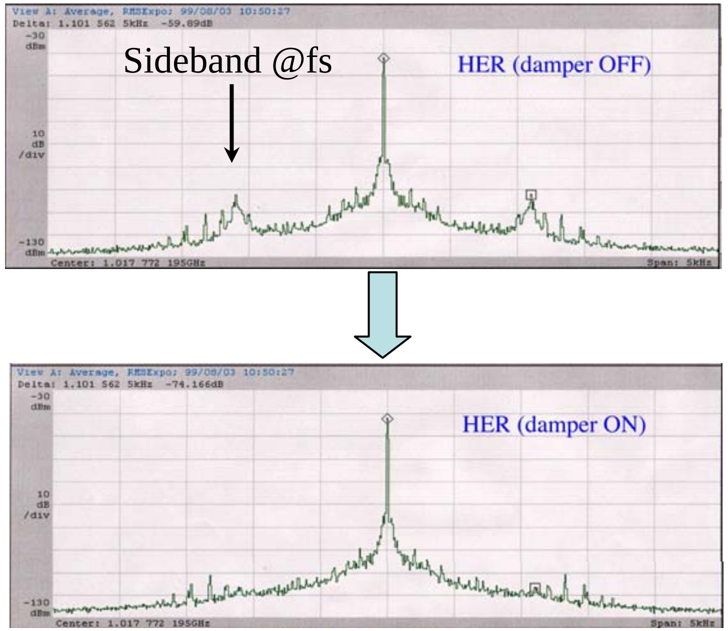




Zero-mode oscillation

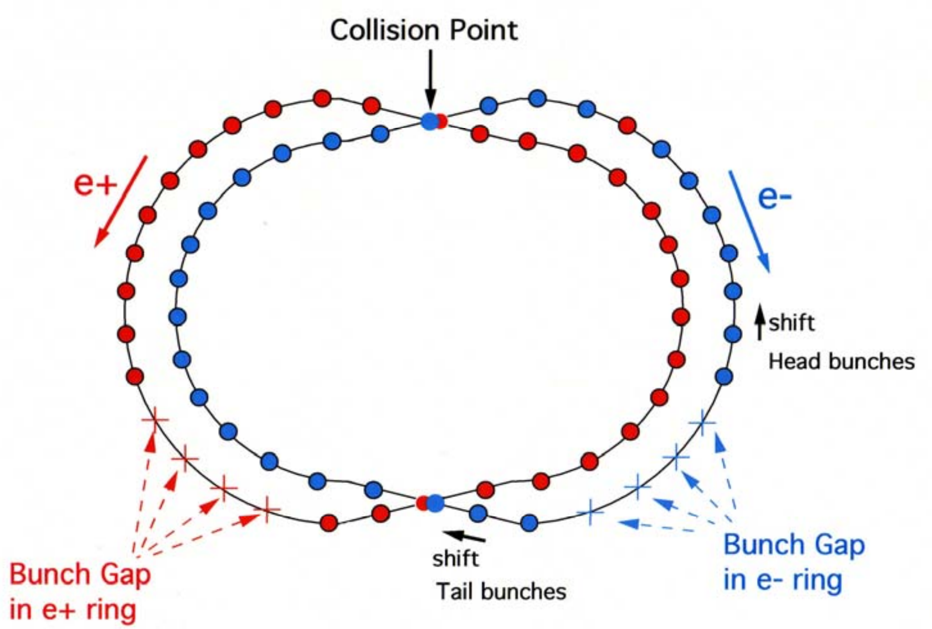
- At the beginning we observed zero-mode synchrotron oscillation even at a low beam current.
  - The amplitude was about 0.5 degree p-p.
  - It is probably caused by noise in the RF reference line system.
- The amplitude is reduced by 15dB by the zero-mode damper.

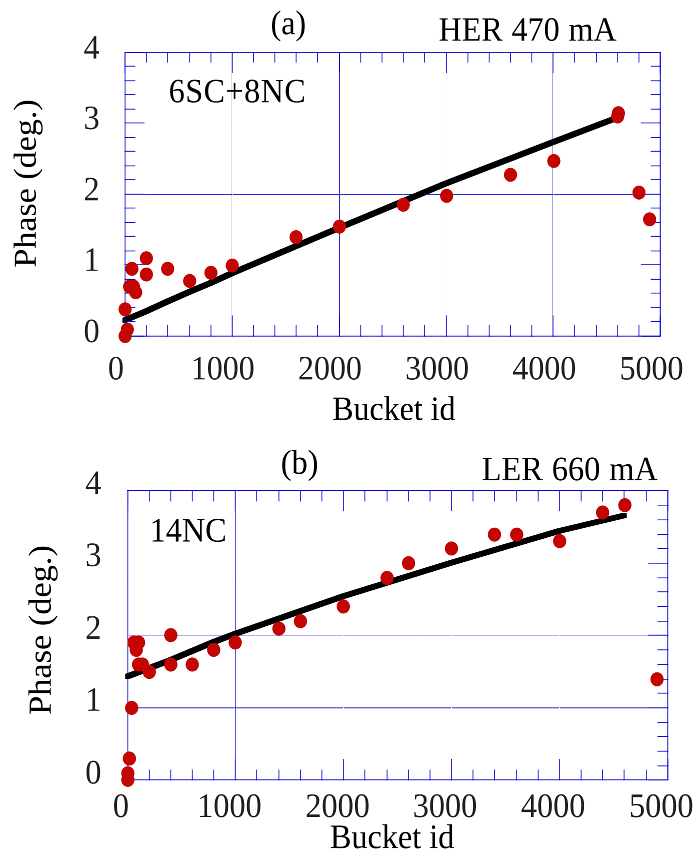




Bunch-gap transient

- 5% of the ring is not filled with bunches (abort gap).
- Longitudinal position is modulated along the bunch train.





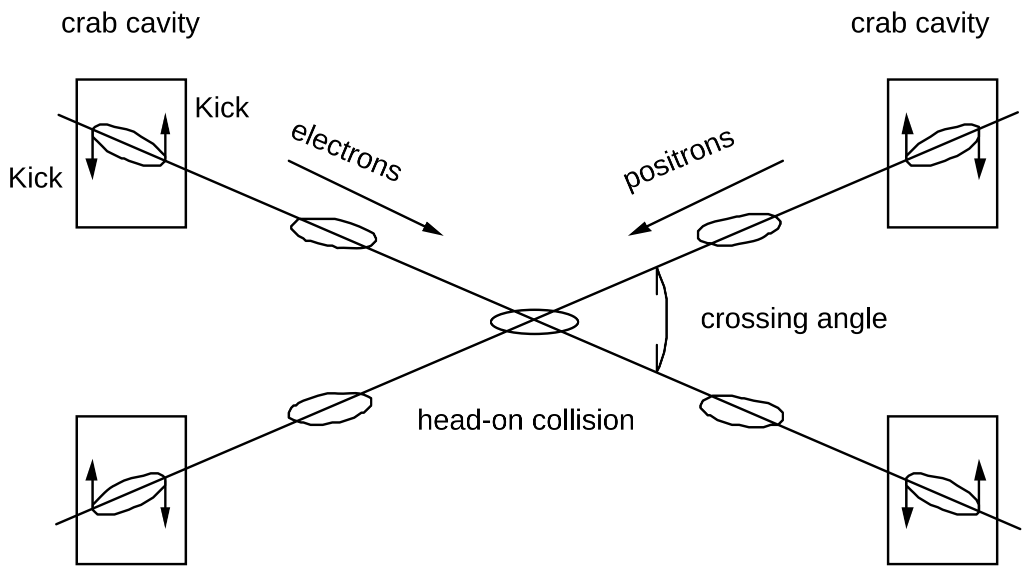
Phase modulation along the train (simulation and measurement).

Upgrade projects

- Crab crossing
  - Superconducting crab cavities will be installed in KEKB next year to conduct crab-crossing experiment.

- SuperKEKB
  - Increase luminosity by 20〜40 times.
  - Design report has been completed.
  - Letter Of Intent has been circulated.

Crab crossing

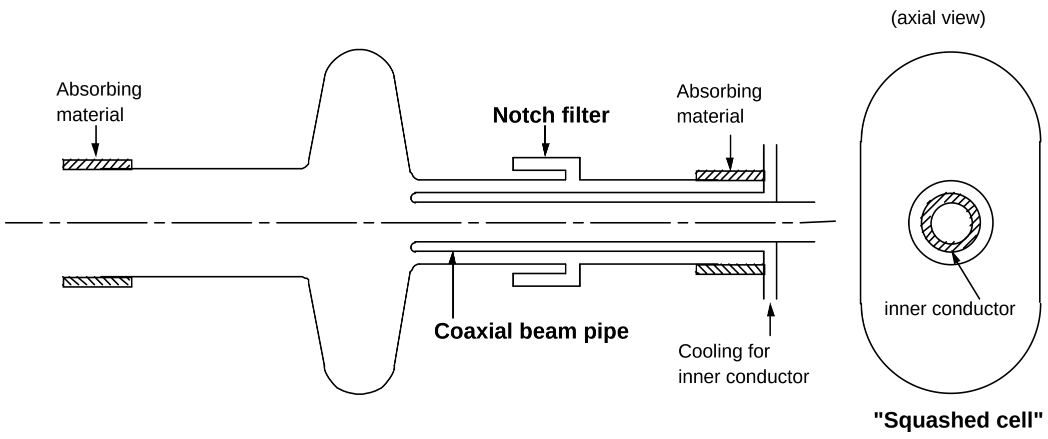


Palmer for LC (1988)
Oide and Yokoya for storage rings (1989)

Recent simulations showed significant increase of luminosity by several times with the crab-crossing.

Crab cavity for KEKB

- Crab cavity for high current beam needs special damped structure.
  - The operating mode is not the lowest frequency mode.
  - Not only HOMs, but also the fundamental mode must be heavily-damped.
- The KEKB crab cavity has unique feature:
  - Squashed cell
  - Coaxial beam pip + notch filter

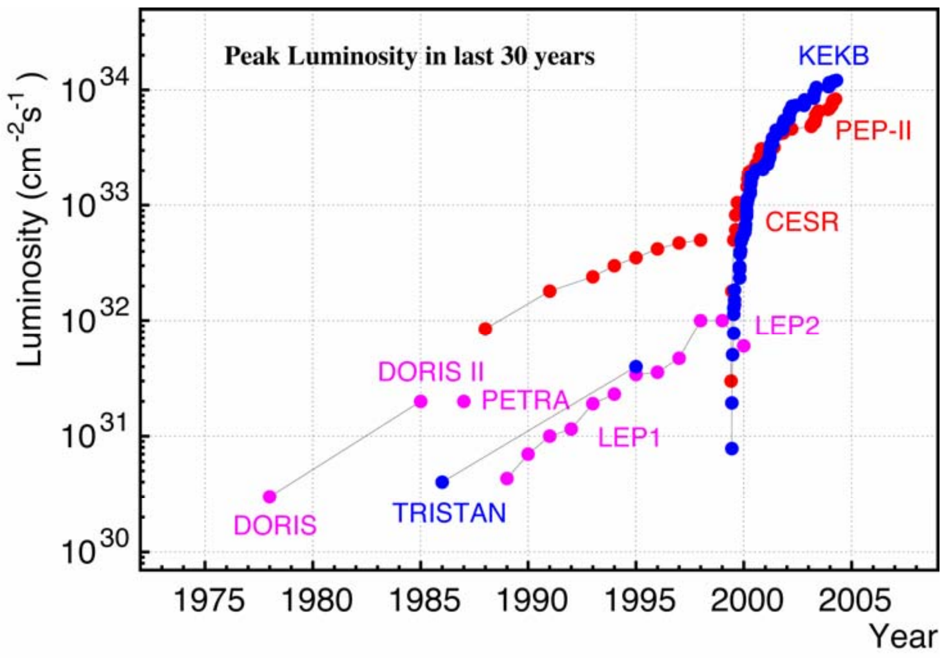


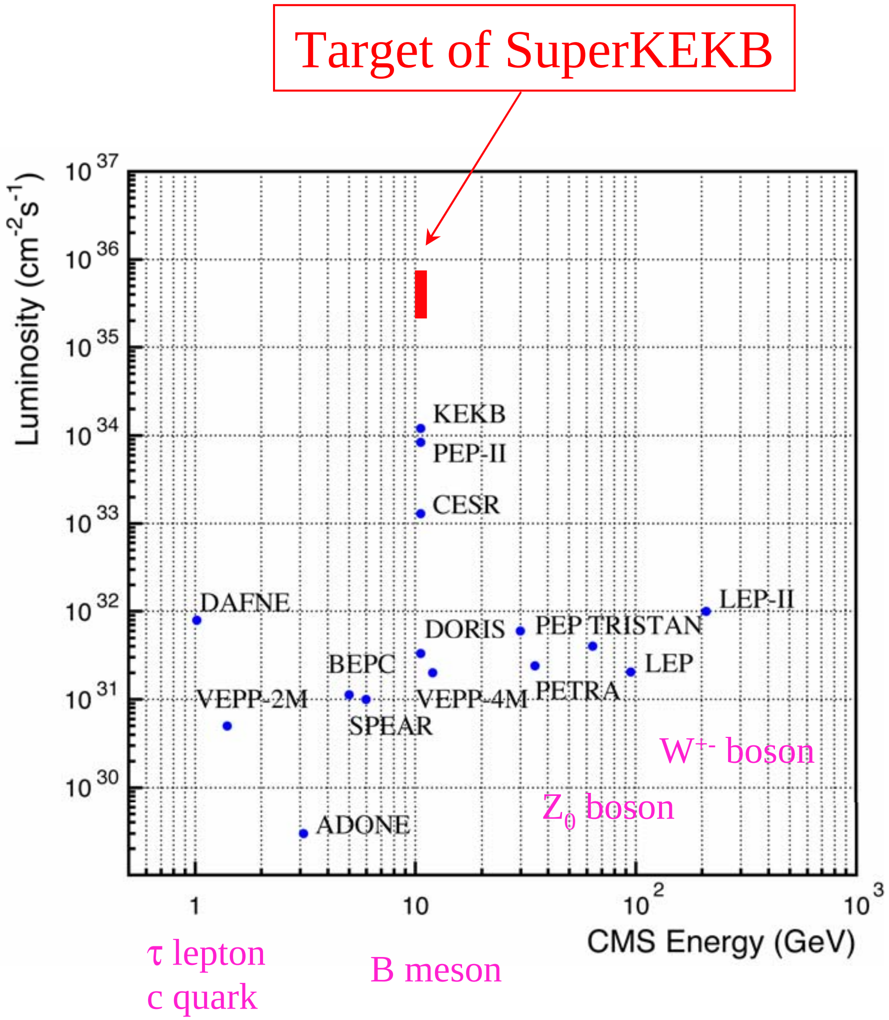
Squashed Crab cavity for B-factories

(K. Akai et al., Proc. B-factories, SLAC-400 p.181 (1992).)

Crabbing mode keeps high-Q value.
All other modes are heavily-damped.

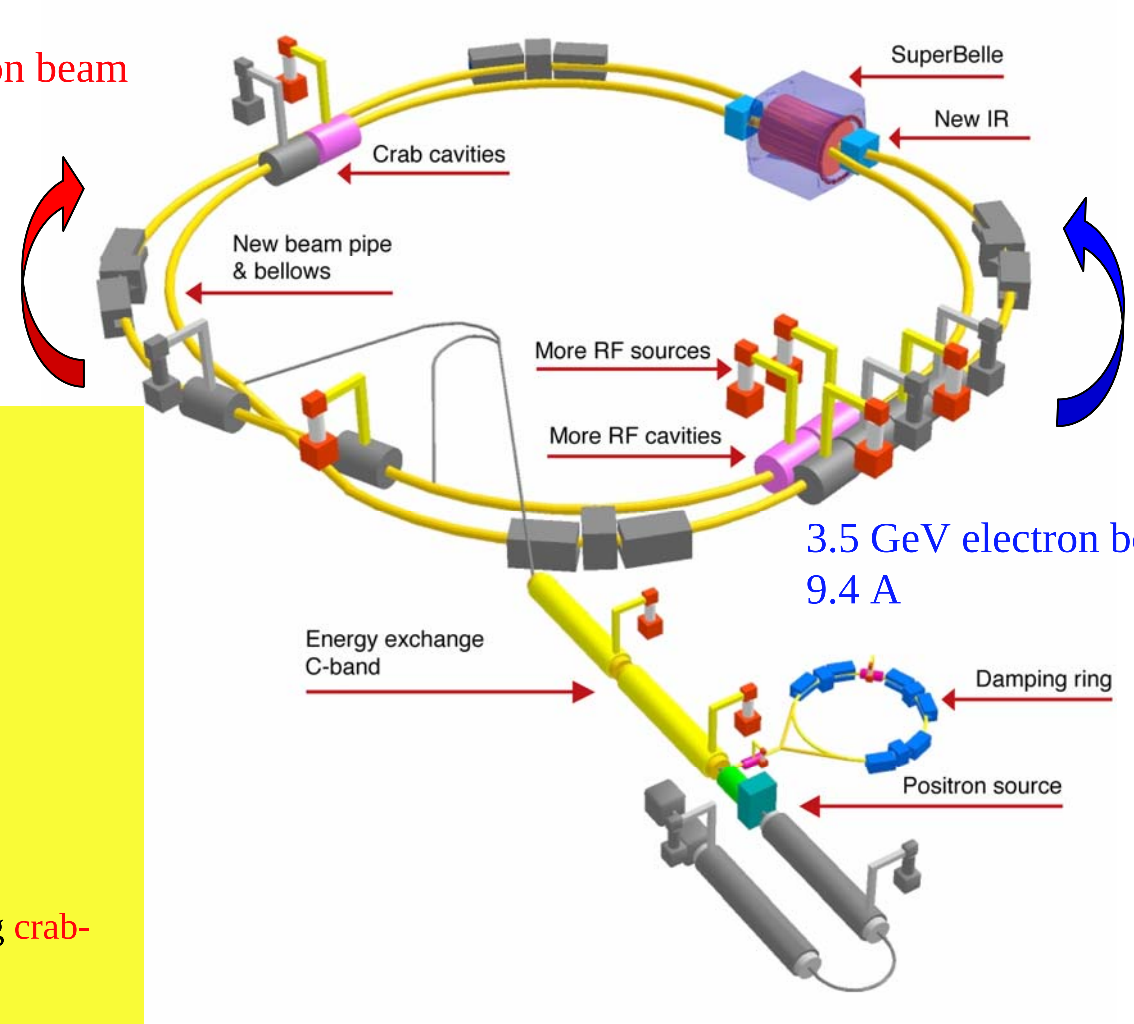
Luminosity of e+e- circular colliders





Concept of SuperKEKB

8 GeV positron beam
4.1 A



3.5 GeV electron beam
9.4 A

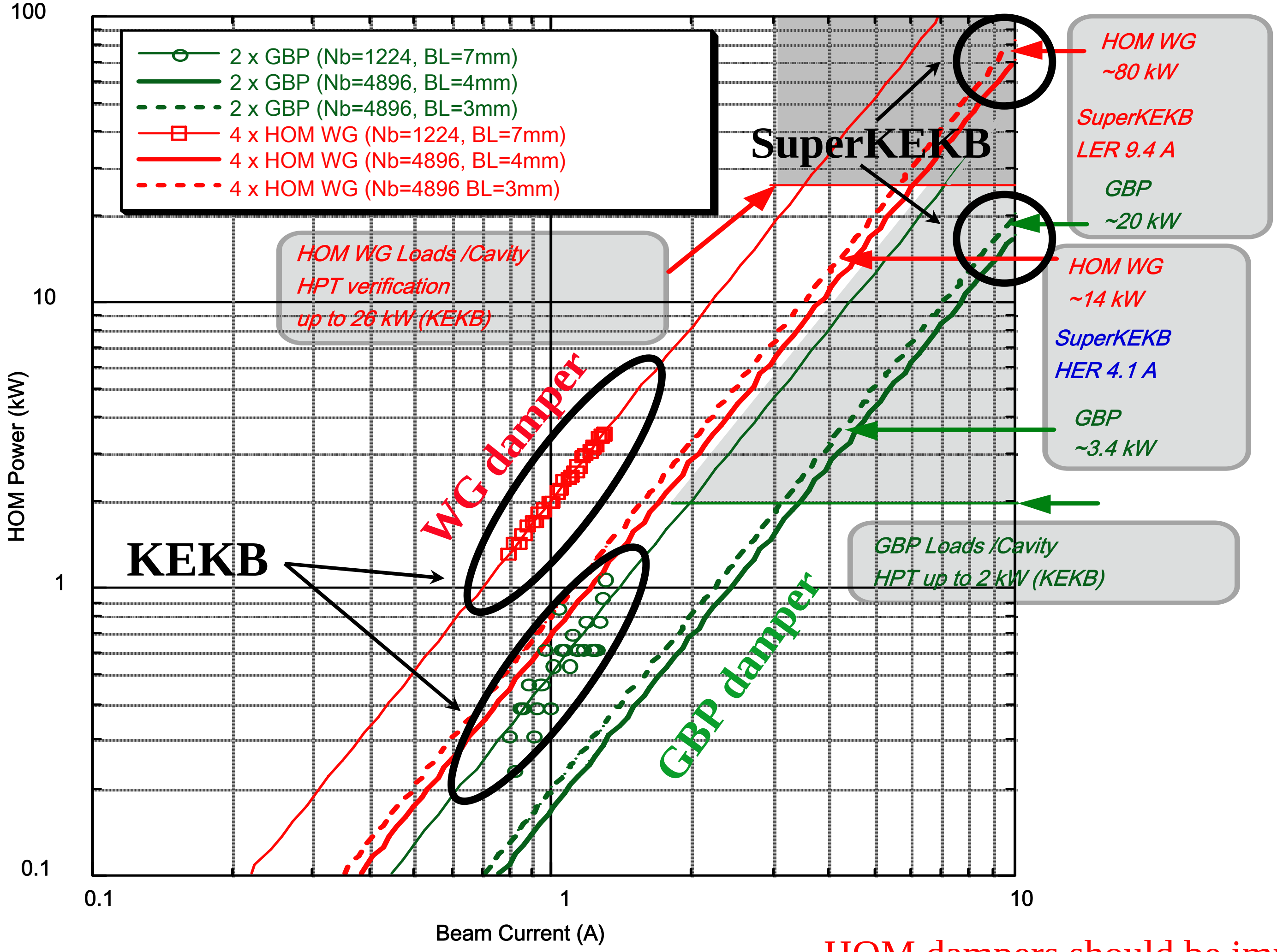
To get $L = 4\times10^{35}$ /cm^{2}s,

- More beam current
  - LER/HER = 1.6A/1.3A → 9.6A/4.1A
- Squeeze βy*
  - βy*= 6mm → 3mm
  - σz= 6mm → 3mm
- Beam-beam parameter
  - ξy=0.05 → 0.14 by adopting crab-crossing

Strategy for SuperKEKB-RF

- 4 times large beam power
  - More than double RF stations are needed (24 → 56).
  - All ARES stations will be converted to (1 cavity) : (1 klystron).
- Modification of the ARES
  - Further increase the stored energy by changing the coupling between A- and S-cavities.
- Improve HOM dampers
  - 50〜80 kW/cavity should be treated.
- Improve LLRF
  - May need to be converted to digital system.
  - Noise in the reference line should be reduced.
  - The -1 mode feedback system should be improved.
    - Even with the modification of ARES, the growth time of the -1 mode instability is as fast as 1 ms.
- Crab cavity for much higher beam current

HOM power of LER-ARES

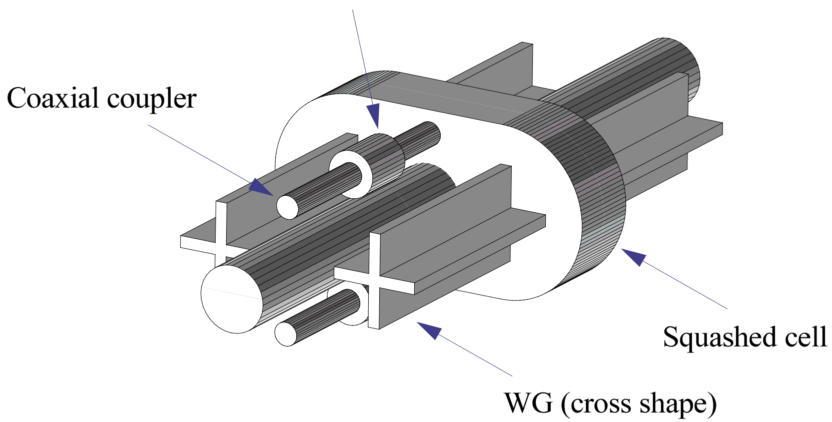


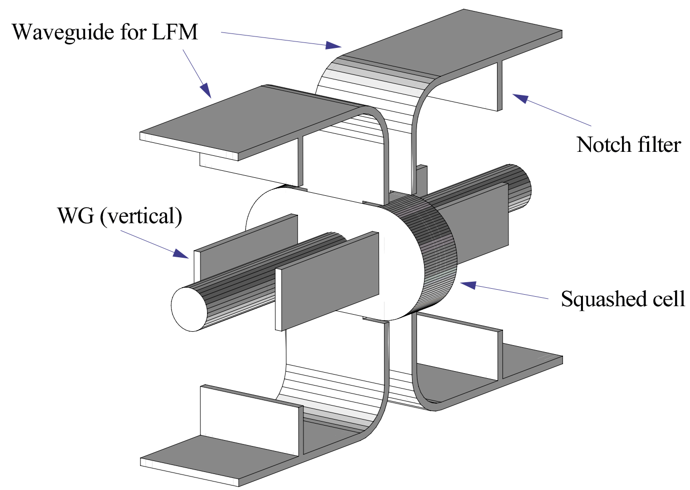
HOM dampers should be improved.

Crab cavity for SuperKEKB

- For SuperKEKB the crab crossing is adopted as a baseline design.
- Much higher beam current (10A)
  - Much heavier damping of HOM and the fundamental mode is needed.
  - Cure for a large amount of HOM power.
- We designed two types of new crab cavity for SuperKEKB.
  - Parasitic impedance is sufficiently reduced.
  - Loss factor is also reduced by less than half.

K. Akai and Y. Morita





Summary

- Continuous effort to improve stability of whole RF system has contributed to high performance of KEKB.

- Owing to high stored energy of cavities, requirements for LLRF is eased compared with conventional cavity system: for example, analog phase and amplitude feedback loops can work satisfactory.

- For upgrading to SuperKEKB, the LLRF may need to be changed including converting to more sophisticated digital system. We expect this LLRF workshop is a good chance to start for future improvements.