Experience with KEKB SC cavities

ILC-DR, KEK

December 18-20, 2007

Takaaki Furuya
KEK

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Contents

KEKB: The strongest e+/e- collider

KEKB

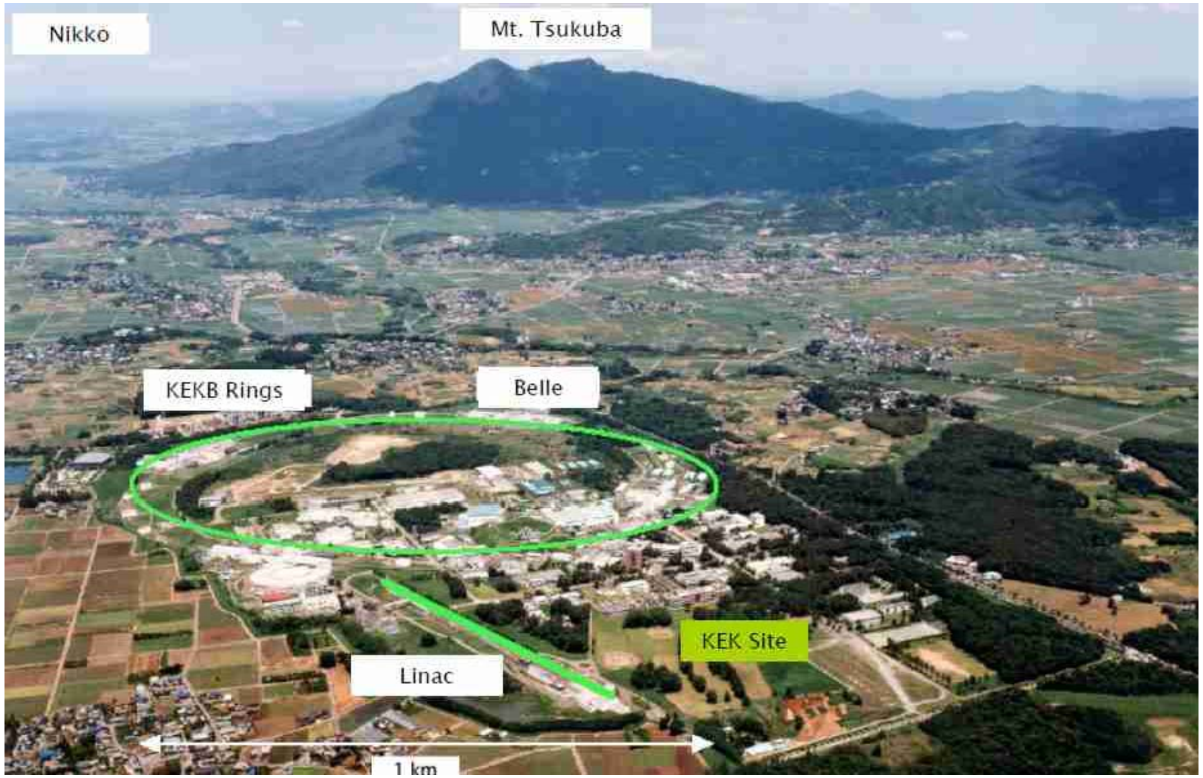
The strongest e+/e- collider for B-meson physics.

Physics run of 8 years since 1999.

Accumulated luminosity of 760 fb^{-1} with the peak luminosity of 1.7×10^{34} $cm^{-2}s^{-1}$.

Design Parameters

	e+/LER	e-/HER
beam energy	3.5 GeV	8 GeV
beam current	2.6 A	1.1 A
harmonic no.	5120	
bunch space	0.6 m	0.6 m
bunch charge	5.2 nC	2.2 nC
horiz. emittance	18 nm	18 nm
(βx,βy) at IP	(33cm, 1cm)	
crossing angle	11 mrad	11 mrad
peak luminosity	1×10^{34} $cm^{-2}s^{-1}$	
luminosity /day	600 pb^{-1}	
circumference	3016 m	



KEKB: The strongest e+/e- collider

Operation history and achieved

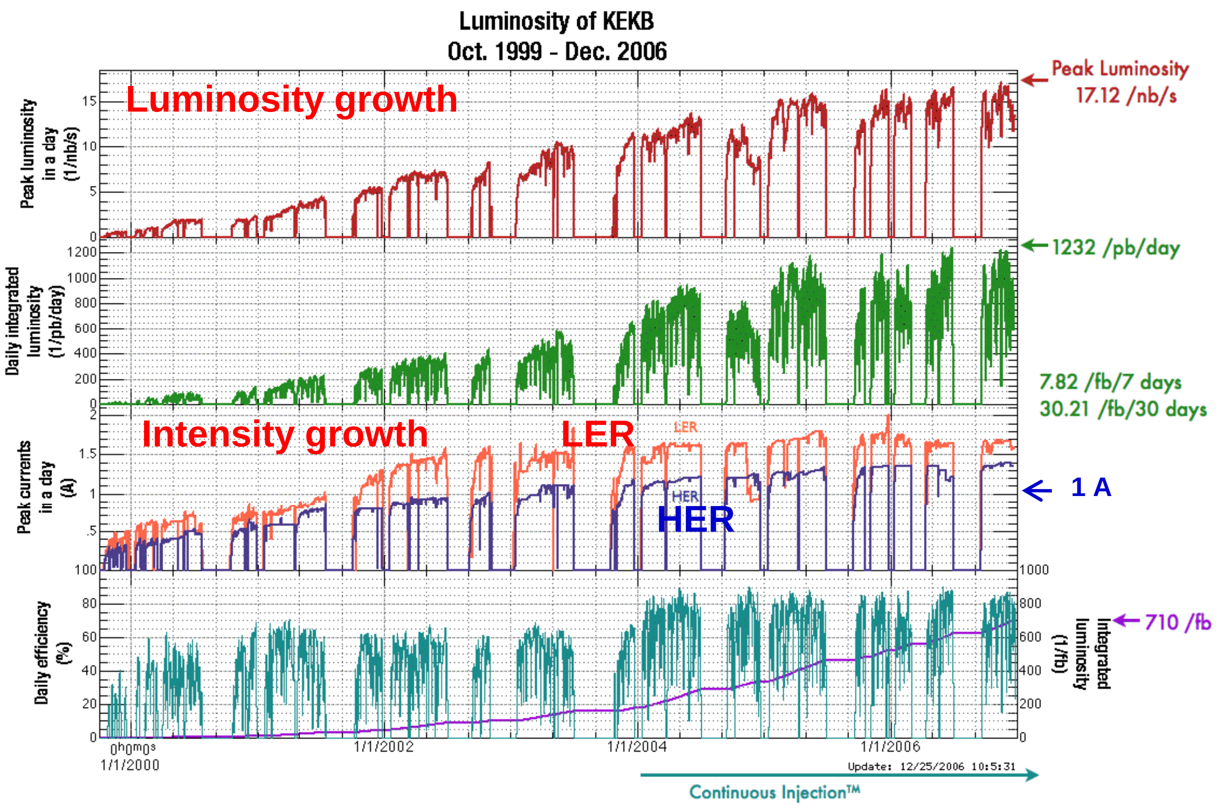
Beam current of 2.0A(LER) and 1.4A(HER).

Because of the electron-cloud instability of LER, N(bunch) was reduced to 1/4 .

Crab crossing with 2 CRABs since 2007.

Achieved Parameters

	e+/LER	e-/HER
beam energy	3.5 GeV	8 GeV
beam current	2.0 A	1.4 A
bunch space	1.8 – 2.4 m	
bunch charge	12 nC	10 nC
Bunch length	7 mm	6 mm
horiz. emittance	18 nm	24 nm
(βx,βy) at IP	(59cm, 0.65cm)	
crossing angle	11 mrad	11 mrad
peak luminosity	1.7×10^{34} cm^{-2}s^{-1}	
luminosity /day	1237 pb^{-1}	
circumference	3016 m	



RF system of KEKB

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◆ RF system for an ampare-class beam

LER: 20 ARES (NC: Accelerator with Resonantly coupled Energy Storage).

low RF voltage & heavy beam loading due to damping wigglers.

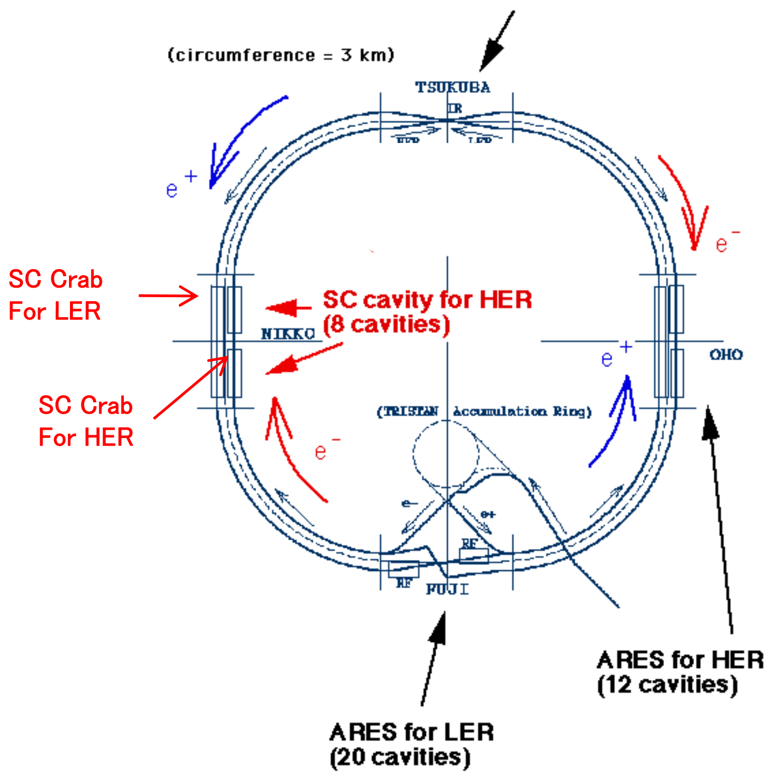
HER: combination of 8 Damped SC & 12 ARES.

high RF voltage & SR loss.

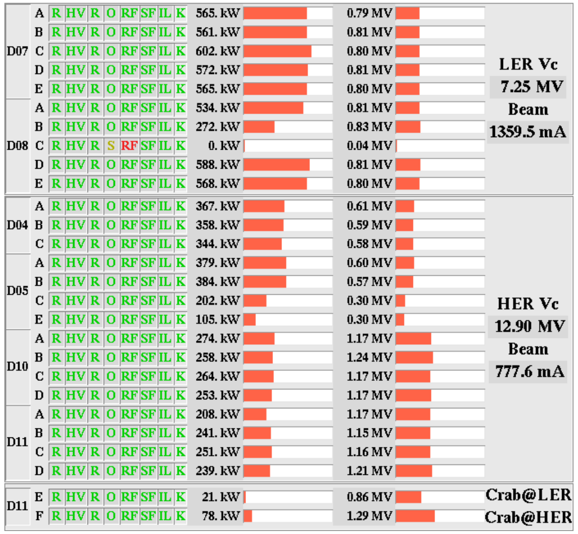
Accelerating RF of KEKB (design)

	LER	HER	
Beam current (A)	2.6	1.1	
SR loss (MV/turn)	1.5	3.5	
total RF voltage (MV)	5 - 9	9 - 16	
frequency (MHz)	508.887		
type of cavity	ARES	ARES	SC
No. of cavities	20	12	8
Vc/cavity (MV/cav)	0.4 – 0.5	0.3 – 0.4	1 -2
No. of klystron (1MW)	10	6	8
beam loading (kW/cav)	200	170	250

RF of KEKB



1MW klystron



D07	A	R HV R O RF SF IL K	565. kW	0.79 MV	
	B	R HV R O RF SF IL K	561. kW	0.81 MV	
	C	R HV R O RF SF IL K	602. kW	0.80 MV	
	D	R HV R O RF SF IL K	572. kW	0.81 MV	LER Vc
	E	R HV R O RF SF IL K	565. kW	0.80 MV	7.25 MV
D08	A	R HV R O RF SF IL K	534. kW	0.81 MV	Beam
	B	R HV R O RF SF IL K	272. kW	0.83 MV	1359.5 mA
	C	R HV R S RF SF IL K	0. kW	0.04 MV	
	D	R HV R O RF SF IL K	588. kW	0.81 MV	
	E	R HV R O RF SF IL K	568. kW	0.80 MV	
D04	A	R HV R O RF SF IL K	367. kW	0.61 MV	
	B	R HV R O RF SF IL K	358. kW	0.59 MV	
	C	R HV R O RF SF IL K	344. kW	0.58 MV	
D05	A	R HV R O RF SF IL K	379. kW	0.60 MV	
	B	R HV R O RF SF IL K	384. kW	0.57 MV	
	C	R HV R O RF SF IL K	202. kW	0.30 MV	HER Vc
	E	R HV R O RF SF IL K	105. kW	0.30 MV	12.90 MV
D10	A	R HV R O RF SF IL K	274. kW	1.17 MV	Beam
	B	R HV R O RF SF IL K	258. kW	1.24 MV	777.6 mA
	C	R HV R O RF SF IL K	264. kW	1.17 MV	
	D	R HV R O RF SF IL K	253. kW	1.17 MV	
D11	A	R HV R O RF SF IL K	208. kW	1.17 MV	
	B	R HV R O RF SF IL K	241. kW	1.15 MV	
	C	R HV R O RF SF IL K	251. kW	1.16 MV	
	D	R HV R O RF SF IL K	239. kW	1.21 MV	
D11	E	R HV R O RF SF IL K	21. kW	0.86 MV	Crab@LER
	F	R HV R O RF SF IL K	78. kW	1.29 MV	Crab@HER

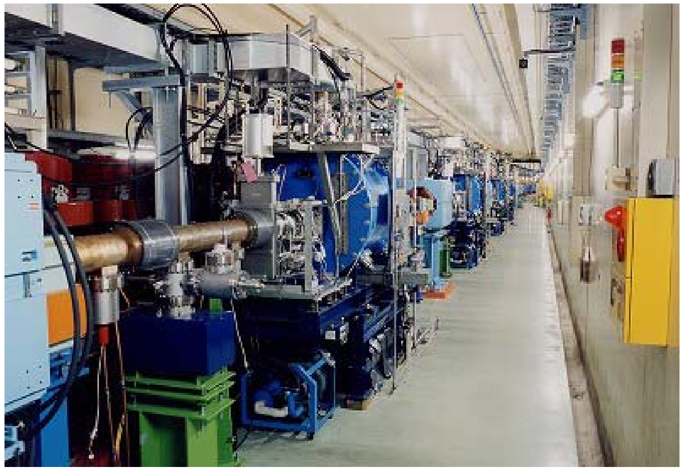
Klystrons of KEKB

10 klystrons for ARES (LER)

7 klystrons for ARES (HER)

8 klystrons for SC (HER)

2 klystrons for Crab



SC accelerating cavities in NIKKO

SC crab cavities in NIKKO

ARES in FUJI

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Accelerating SC of KEKB

◆ Operation history of Accelerating SC

1998 Commissioning with 4 SC's in D11-site.
1999 Coupler power test with beam:
380kW was delivered to the beam.
Physics run start.
2000 Installation of the next 4-cavities in D10-site.
2001 L_{peak}= 6.9 x 10^{33} $cm^{-2}s^{-1}$
with beams of HER/LER = 0.8A/1.0 A.
HOM of each SC reached 5kW.
2002 L_{peak} = 8.2 x 10^{33} $cm^{-2}s^{-1}$ with HER beam of 1 A.
2003 L_{peak} = 1.06 x 10^{34} $cm^{-2}s^{-1}$
The max. current of HER reached 1.1 A in
1184 bunches.
HOM of each SC reached 10kW.
Capacity of cooling water was increased
to 20kW.
SC-Vc test up to 2MV using D11B cavity.
L_{peak} = 1.13 x 10^{34} $cm^{-2}s^{-1}$
with beams of HER/LER = 1.18A/1.56 A
2004 Continuous Injection mode
1.25A in 1293 bunches induced 16kW of HOM.
2005 Lpeak = 1.5 x 10^{34} $cm^{-2}s^{-1}$ with 1.27A(HER)
2006 Lpeak = 1.71 x 10^{34} $cm^{-2}s^{-1}$ with 1.40A (HER)
integral luminosity has reached 700 fb^{-1}

Summary of achieved performances

	design	achieved
No. of cavities	8	8
Max. beam current (A)	1.1	1.40 (127%)
No. of bunches	5000	1389
bunch charge (nC)	2.2	10.1
Bunch length (mm)	4	6 - 7
RF voltage (MV/cavity)	1.5	1.2 - 2
unloaded Q at 2MV	1E+09	0.3 -1 E+09
beam loading (kW/cav)	>250	350 - 400
HOM loading (kW/cav)	5	14 - 16

Module of accelerating SC

- **Cryomodule of the accelerating cavity**

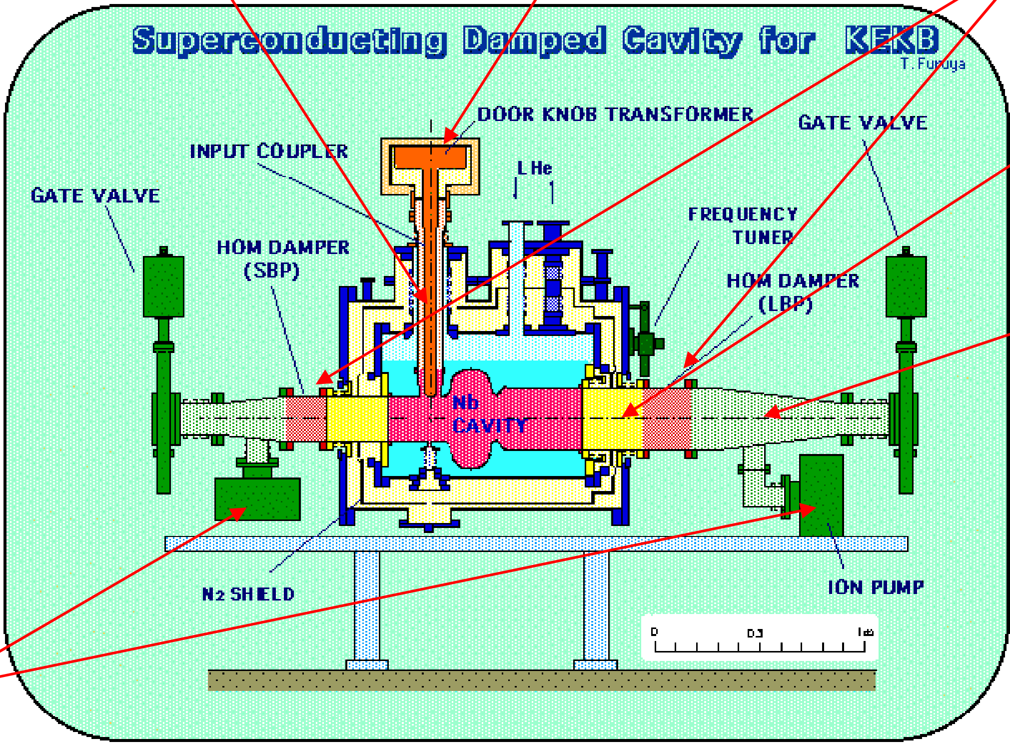
Coaxial type power coupler

Doorknob with bias voltage(±2kV)

Cylindrical ferrite damper (4 mm in thick)

Large diameter for HOM extraction (300 mm)

Long taper to reduce a loss factor (60 cm)



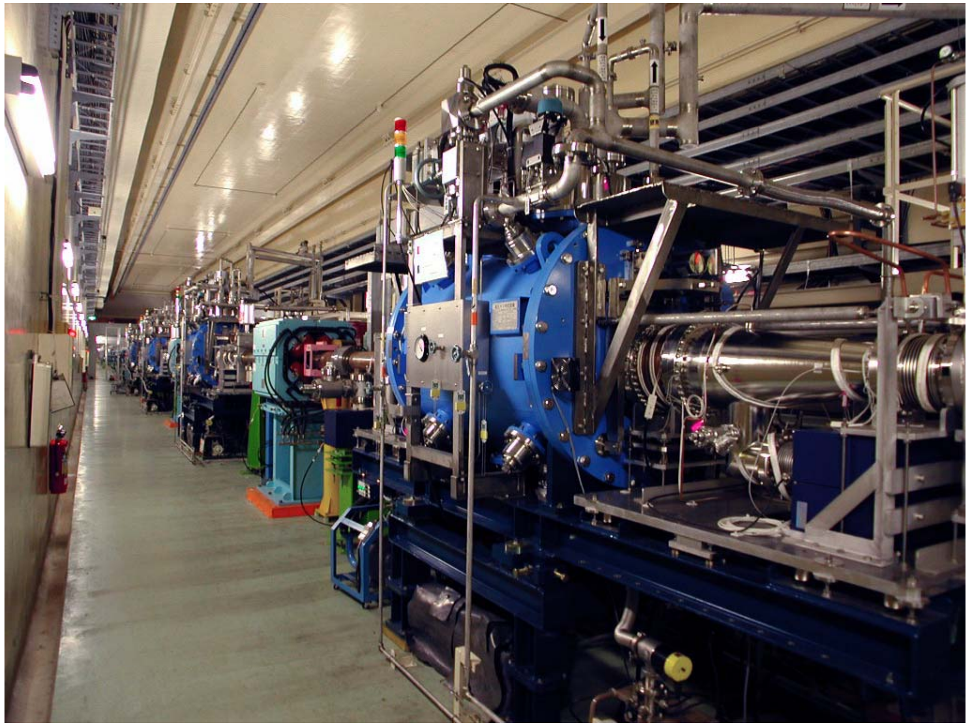
Ion pump (400 L/sec)

509 MHz single cell cavity

Number of cavity: 8
Accelerating gap: 0.243 m
R/Q: 93 ohm
Length of the module: 3.7 m
Beam hight: 1500 mm
Total hight: 3000 mm (not including TR Tube)
Operating temperature: 4.4K

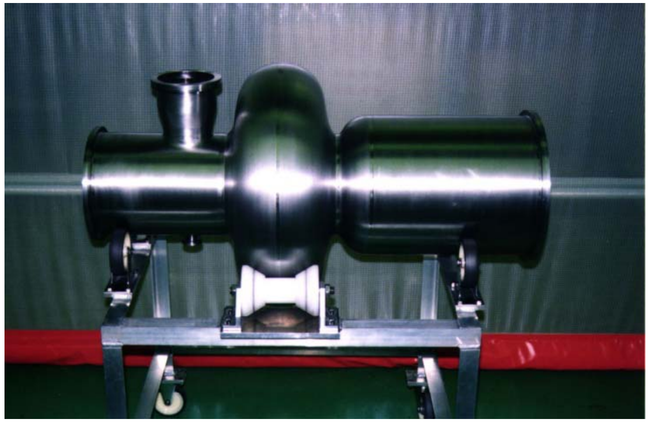
Module of accelerating SC

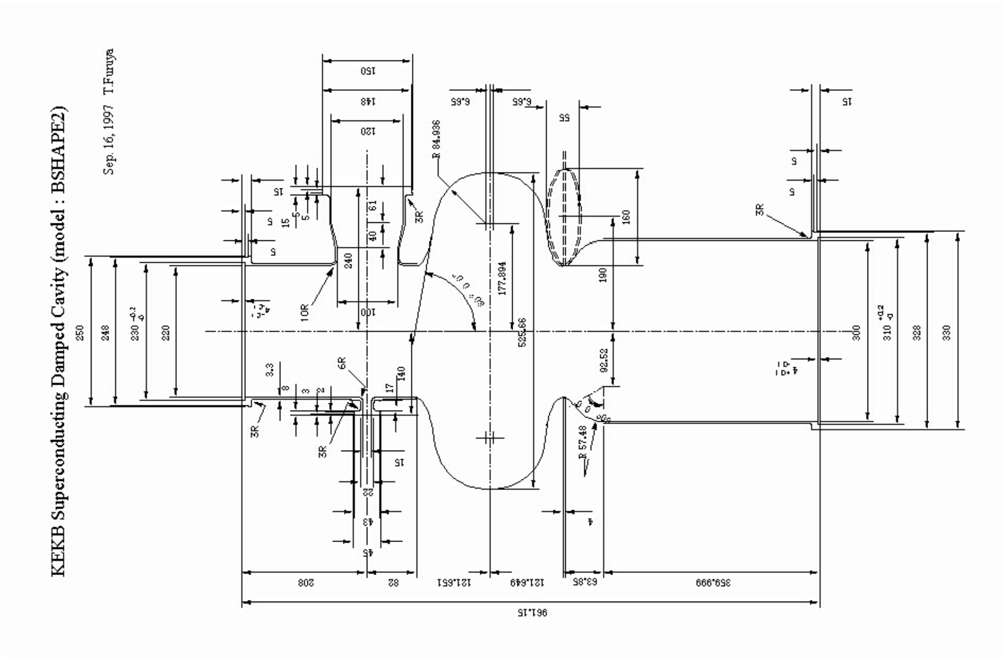
◆ Important components: Nb cavity



Cavity

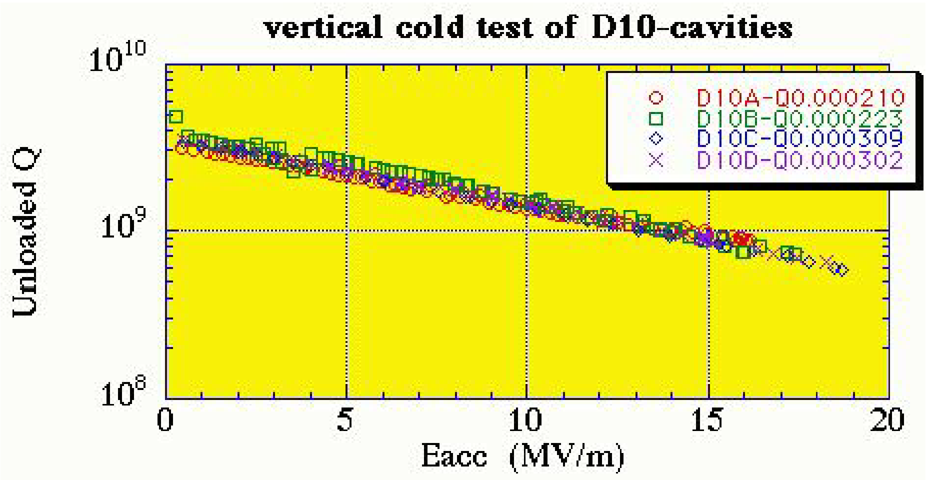
- Nb single-cell
- Frequency: 508.887 MHz
  motor tuner: ~400 kHz
  piezo tuner : 6 kHz
- Gap length: 0.243 m
- R/Q : 93 Ohm
- Esp/Eacc: 1.84
- Total length: 3.7 m

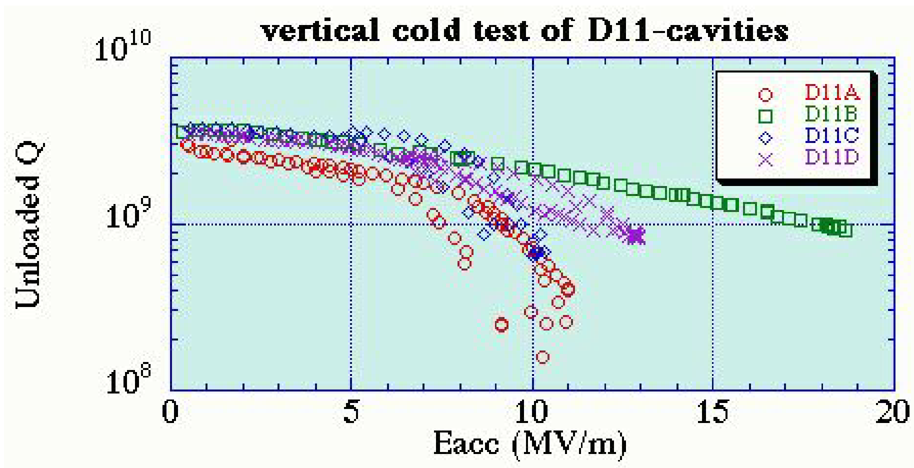




Shape parameters

Frequency:	508.887 MHz
R/Q:	93 ohm
Geometrical factor:	253 ohm
Esp/Eacc:	1.84
Hsp/Eacc:	40.3 G/(MV/m)
Iris dia.:	220 mm
Beam pipe dia.	300 mm
Ferrite thickness:	4 mm





Vertical test results

Module of accelerating SC

◆ Important components: power coupler

Input Couplers

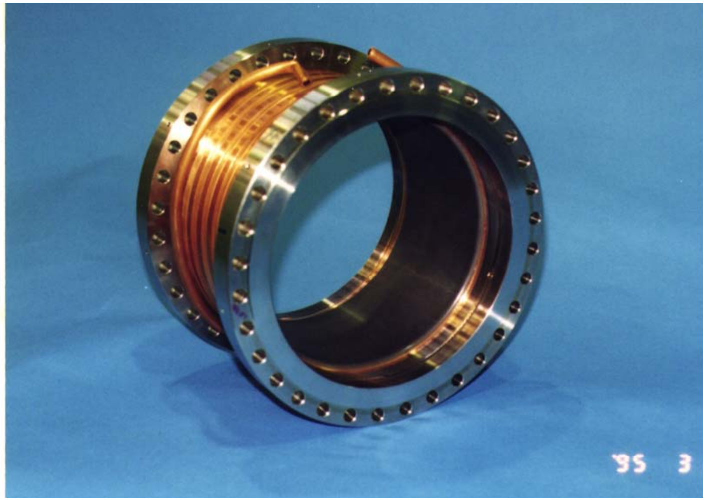
- handling power of 400 kW(CW)
- Qext = 5×10^4
- ceramic disk of 152dia.
- water cooling of inner and
  He gas cooling of outer conductor
- DC voltage of 2 kV between inner
  and outer conductors.
- loss at 300kW: 250 – 300 W (ceramic RT)
  200 W (inner RT)
  30 W (outer 4K)
- monitoring of vacuum pressure and arcing.

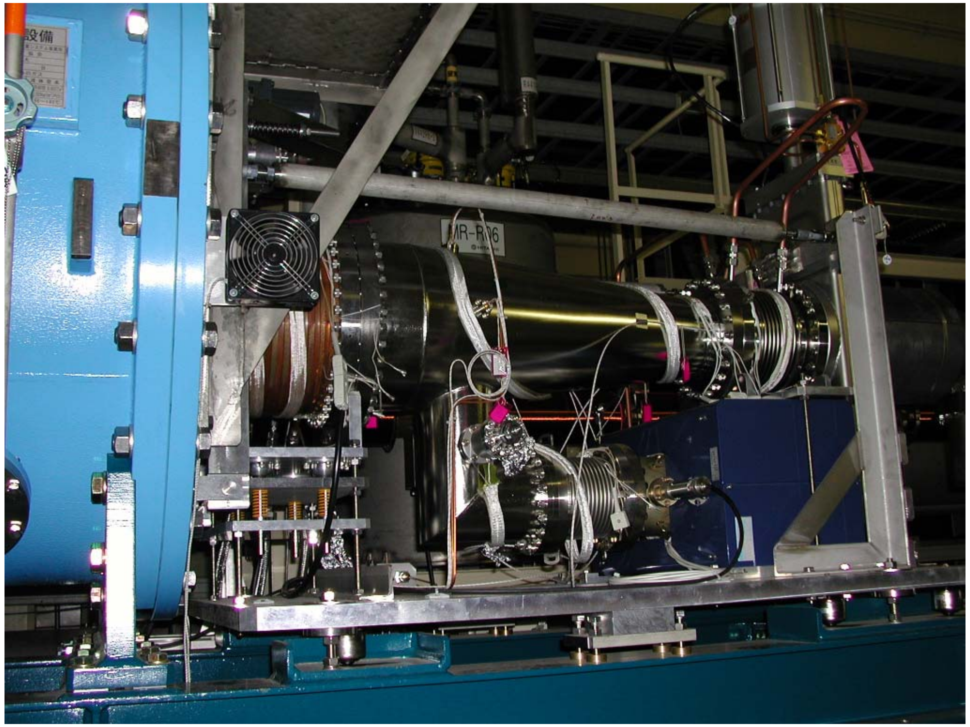
Module of accelerating SC

◆ Important components: HOM absorber

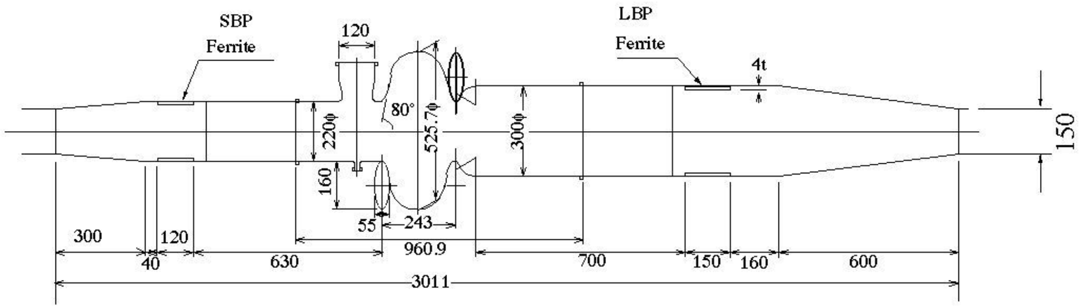
HOM Absorbers

- IB004 Ferrite of 4mm in thickness
- HIP (950℃×1500atm)
- 300dia x 150 mm(LBP)
  220dia x 120 mm(SBP)
- water cooling from out side





HOM damping: optimization of ferrite dampers



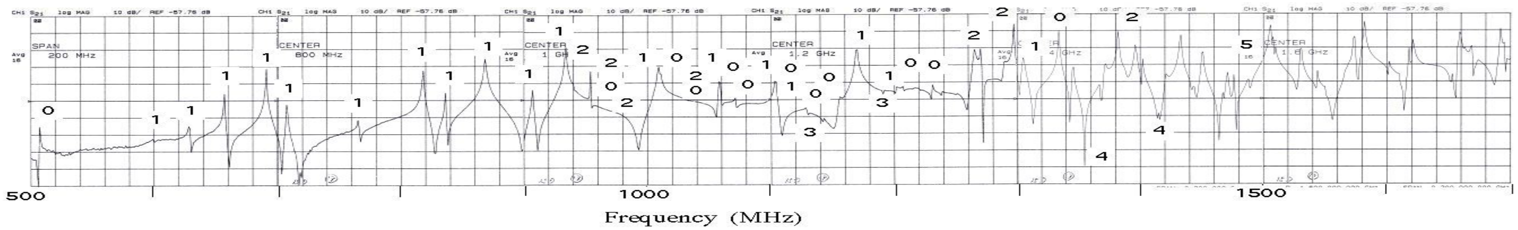
Typical HOM

Mode	Freq. (MHz)	R/Q (ohm)	Q meas.
TM011	1018	7	106
TM020	1027	6	95
TE111	688	6*	145
TM110	705	8*	94

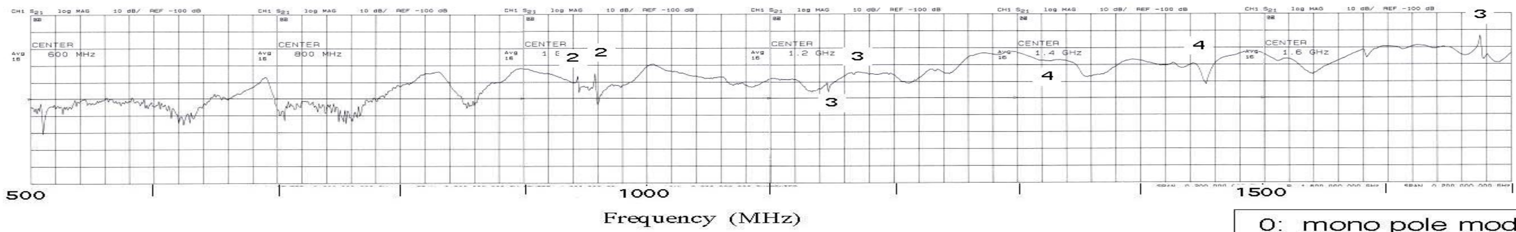
* : R/Q at 5 cm

Mode measurements

Al model cavity without Ferrite



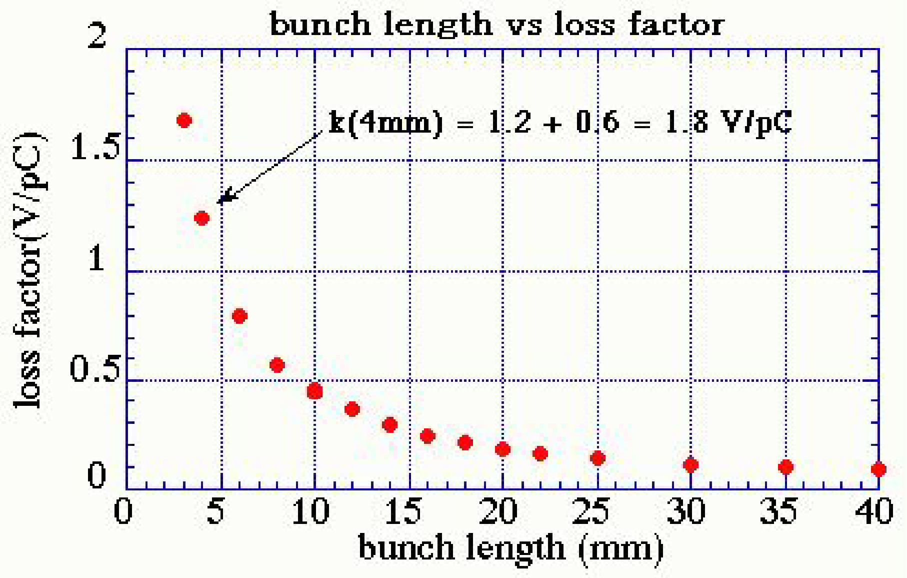
Nb cavity with Ferrite (at Horiz. Test)



0: mono pole mode
1: dipole mode
2: quadruple mode

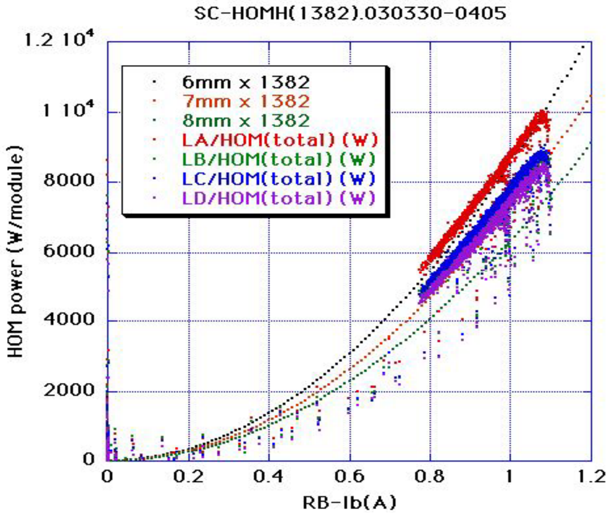
Loss factor:

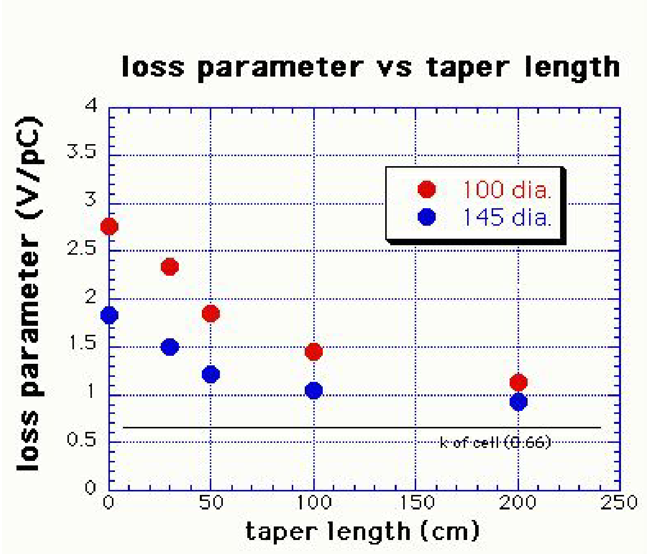
- serious for the short bunch length
- damper itself becomes the source of the loss factor.
- use longer taper to reduce k



$$HOM\ \ power = k \cdot q \cdot I$$

$$k = k_{cavityshape} + k_{damper}$$

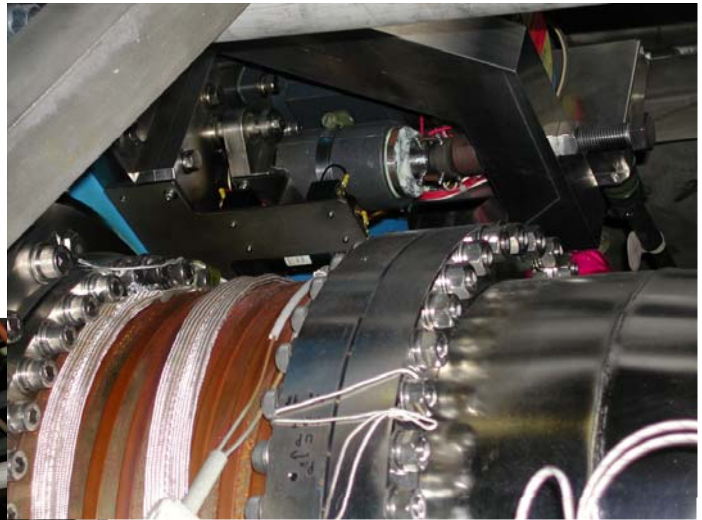


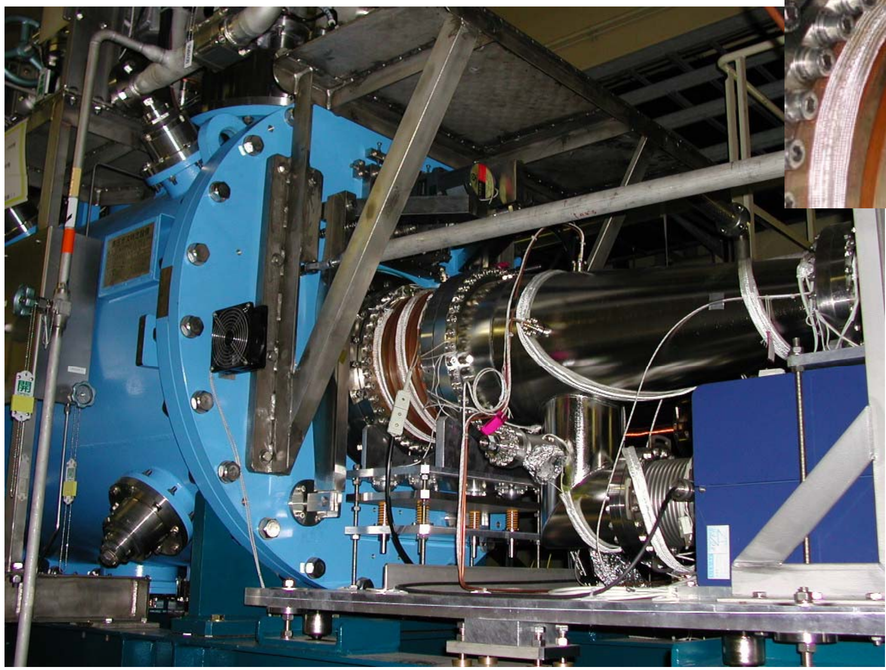


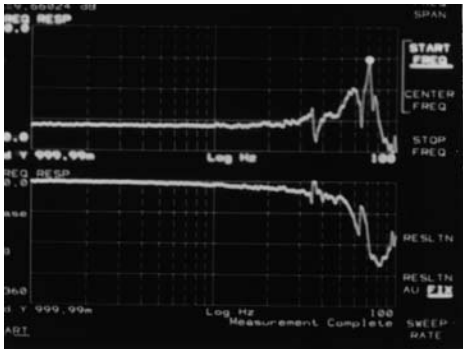
Module of accelerating SC

◆ Important components: frequency tuner

Motor tuner (coarse tuning)
• range of 400 kHz
Piezo tuner (fine tuning)
• tuning range of 6 kHz
• response of 20 Hz limited by the mechanical resonance of 70 Hz





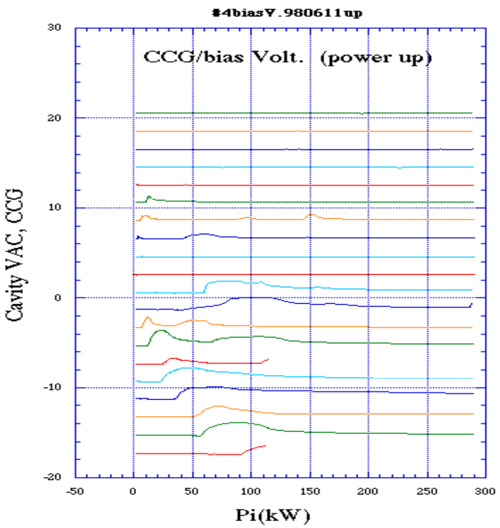


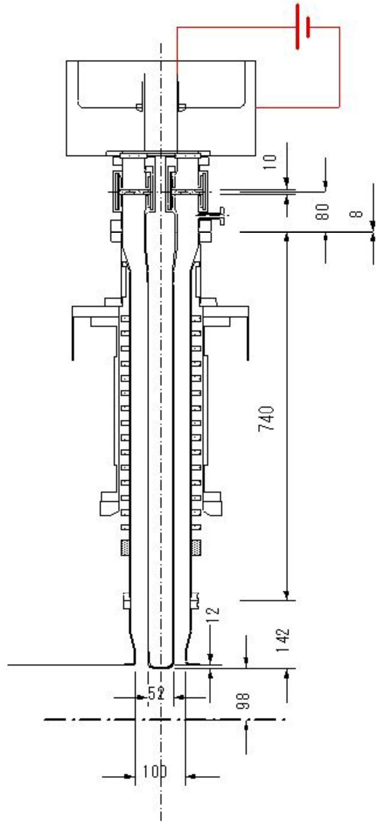
resonance of 70 Hz

Operation of accelerating SC

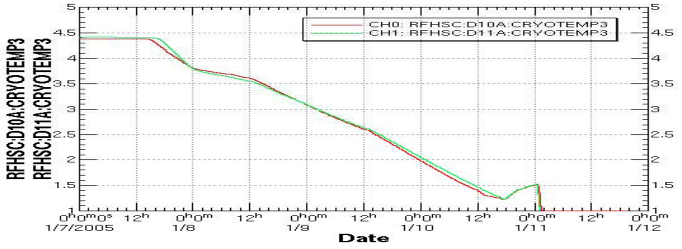
◆ Conditioning and cooling

Coupler conditioning at RT :
with scanning bias voltage to ±2 KV
up to 300 kW under full reflection





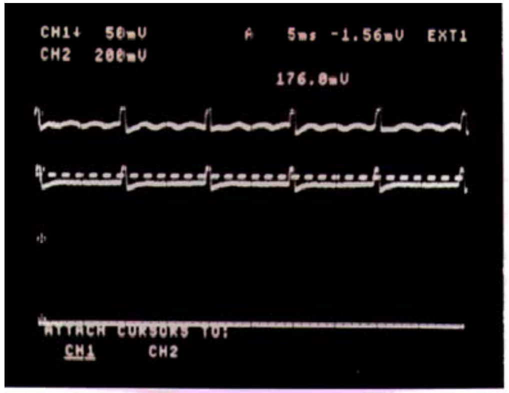
Slow cooling rate of < 4K/hr (4 days)



Cavity conditioning: pulse conditioning
(0.5 ms, 100 Hz)

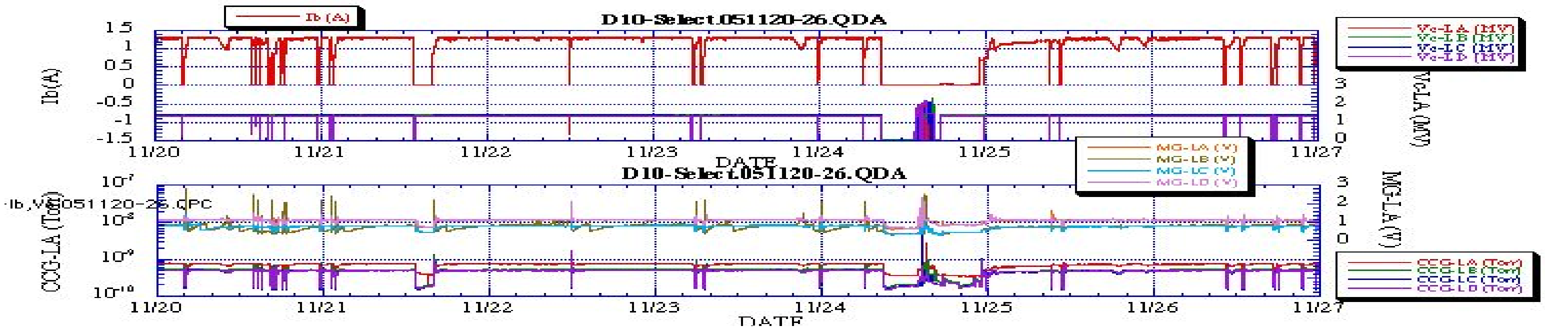
Quench level (dotted) →

GND →

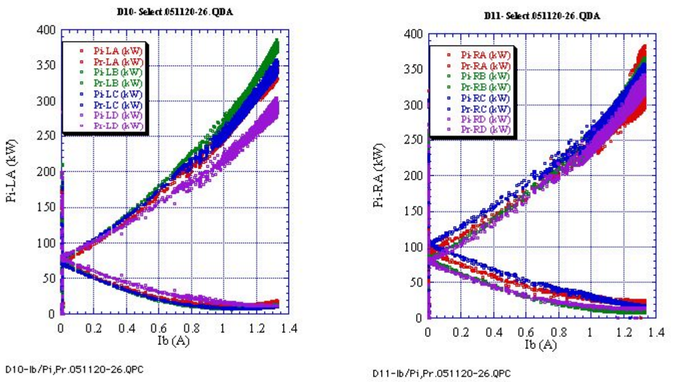


Operation of accelerating SC

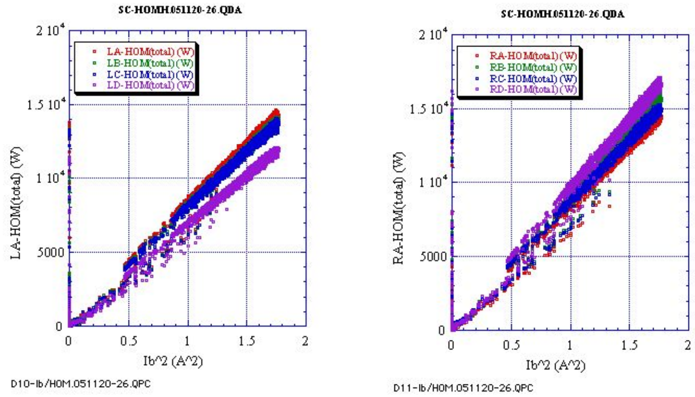
Operation:



- Top-up operation
- Conditioning of 3hrs at a maintenance day of every two weeks.
- When one of the RF cavity trips, the beam has to be aborted immediately to protect the detector against a strong radiation noise.
- Power delivered to the beam by SC cavities is 2.6 MW.
- HOM absorbed by dampers reaches 16 kW/cavity.



Input and reflecting power



Absorbed HOM power

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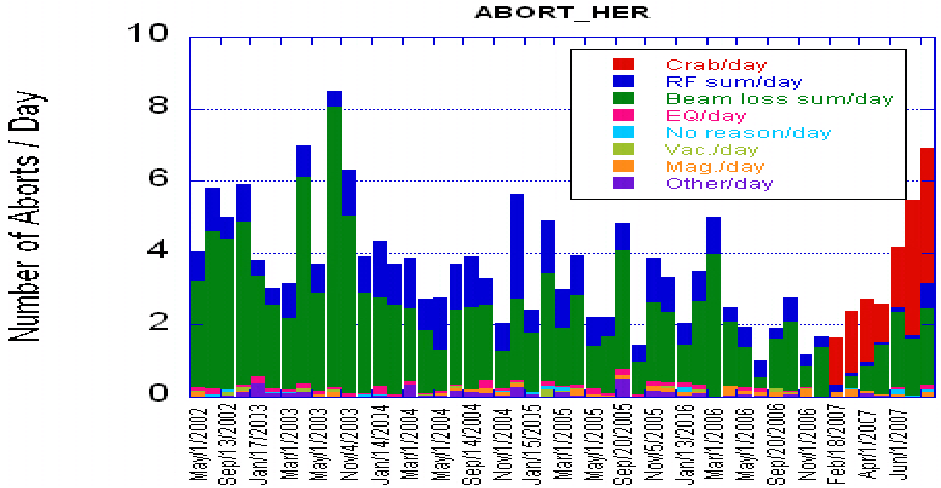
Operation of accelerating SC

◆ Trip:

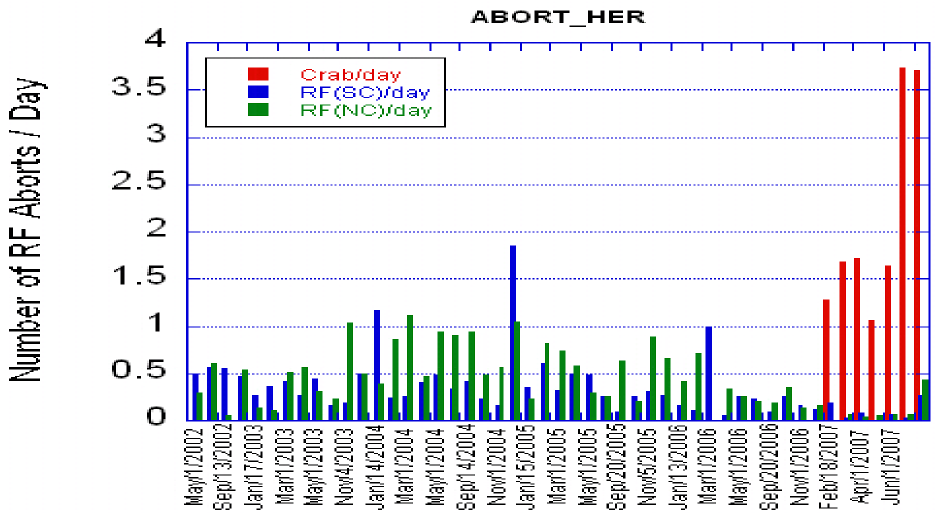
HER: total beam abort/day

Detect and analyze the signals of beam current, RF voltage, beam loss monitor, etc.



HER abort caused by RF system

Trip rate of SC is <0.5/day for 8 SC.
Reduced to <0.1/day under a low beam current of 850 mA.

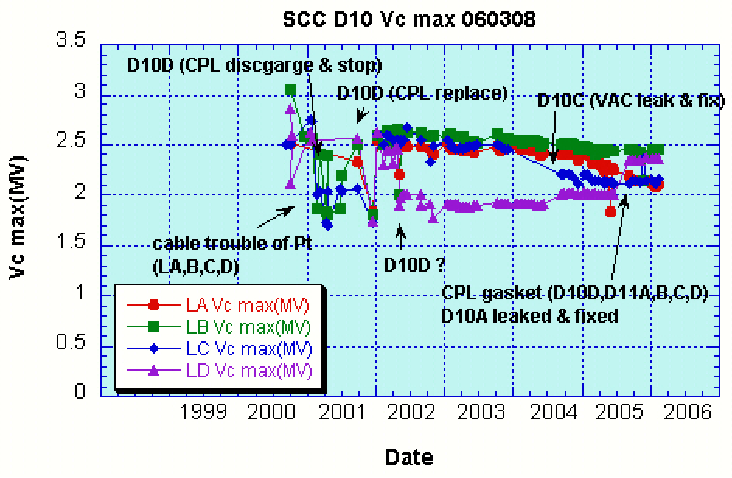


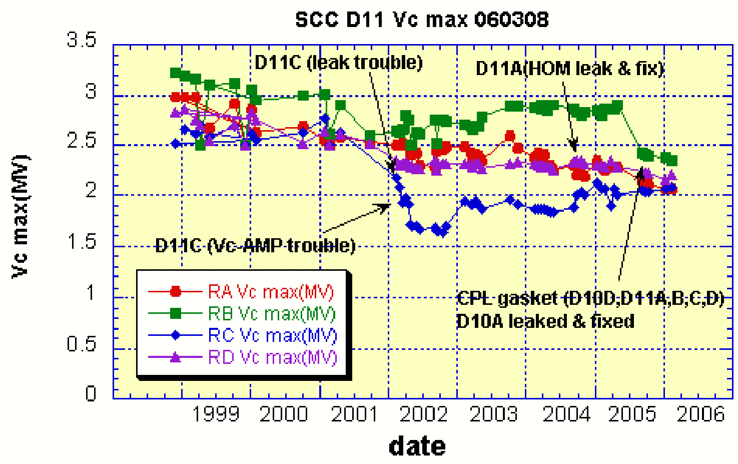
Operation of accelerating SC

◆ Performance: degradation during a long term operation

1) The maximum accelerating voltage

- All of the cavities can provide the accelerating voltage of >2 MV after 7 years operation.
- The voltage of D11C degraded by the vacuum trouble. Some amount of dirty air went into the cavity.
- To increase the coupling, the gasket of input coupler was replaced to a thinner one. D11B degraded after this replacement.





Operation of accelerating SC

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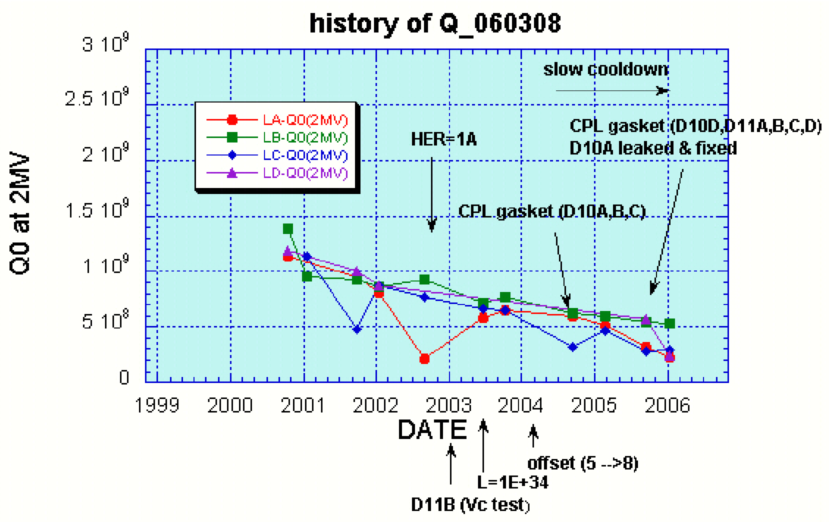
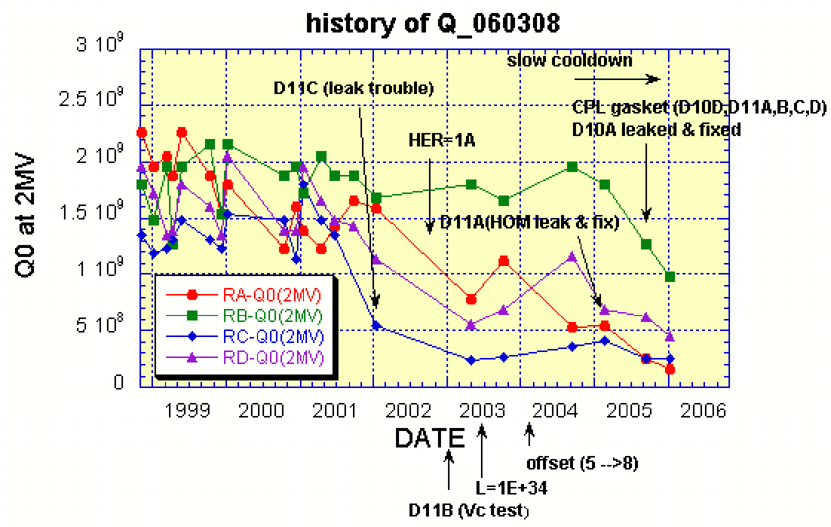
◆ Performance: degradation during a long term operation

2) Unloaded Q

- Unloaded Q degraded to 3-5x10^8 at 2MV (8 MV/m) by the electron emission.
- The Q at the operating voltage (1.4MV) still keep the Q of >1x10^9.
- Baking may recover the performance, but we have to worry about the vacuum leak at the indium seals.
- Huge out gas of the ferrite dampers degrades the cavity performance?





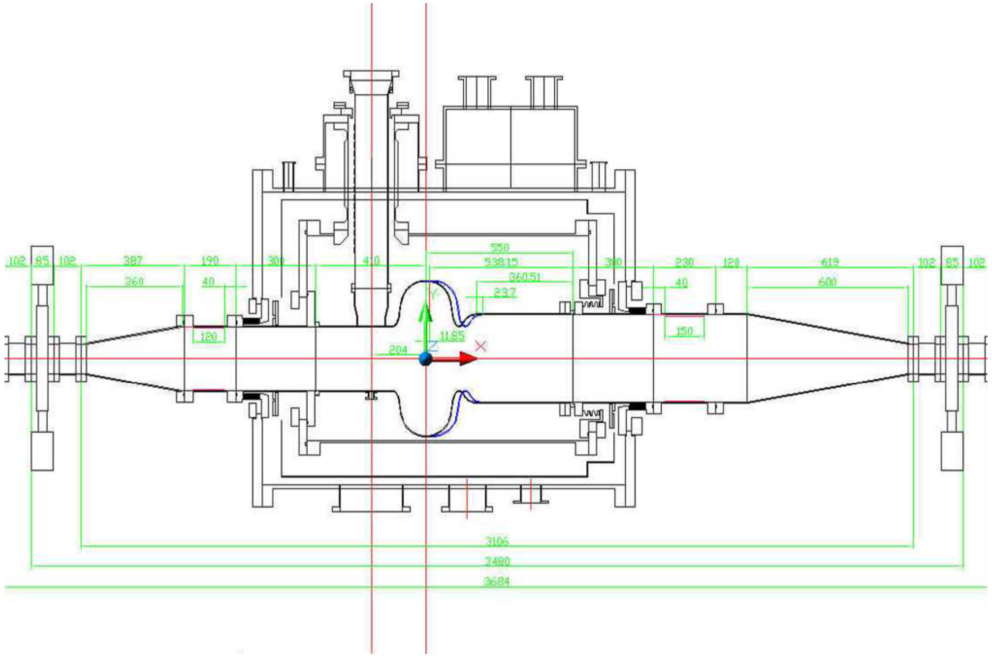
Collaboration with IHEP in Beijing

◆ BEPC-II of IHEP: SC module of 500 MHz

- Upgrading of BEPC (Beijing Electron Positron Collider).
  collision mode: 1.89 GeV, 910 mA + 910 mA
  SR mode: 2.5 GeV, 250 mA
- Use of SC cavities based on KEKB cavity.
- Because of a difference of RF frequency, a slight modification was given to the equator straight. (13.3 mm → 37 mm)

Parameters of Cavity Shape

•Frequency	(MHz)	499.8
•Accelerating gap	(mm)	267
• beam pipe diameter	(mm)	220
•Large beam tube diameter	(mm)	300
•*R/Q*	(Ohm/cavity)	95.3
•Loss factor	(V/pC)	0.075
•*Esp/Eacc*		1.87
•*Hsp/Eacc*	Gauss/(MV/m)	41.1



Collaboration with IHEP in Beijing

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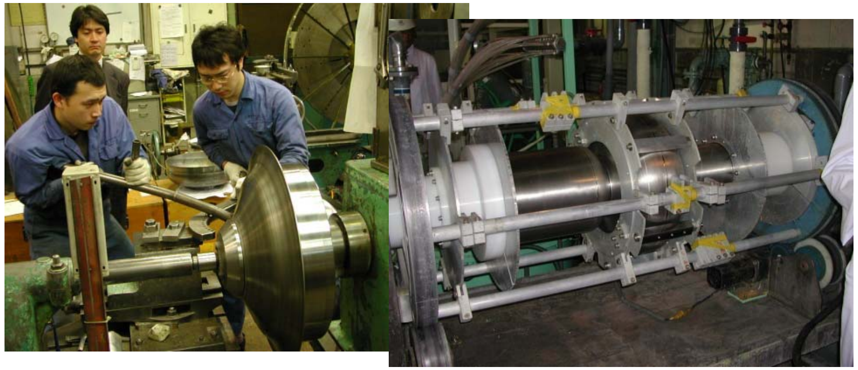
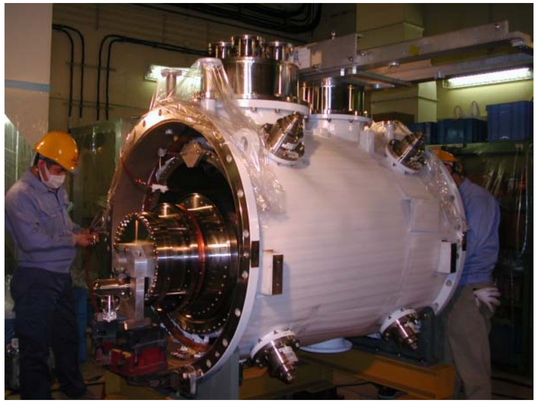
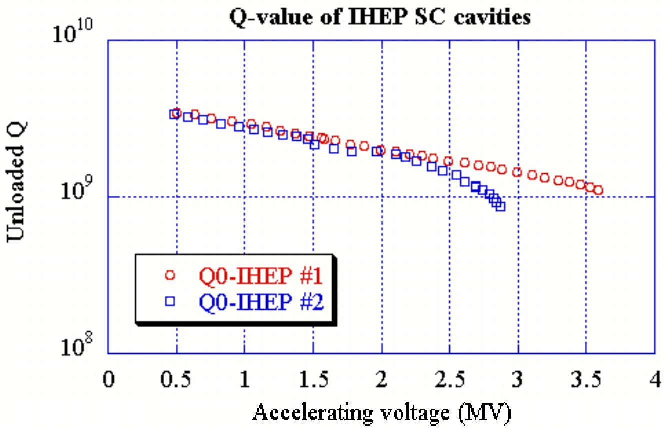
◆ Fabrication and vertical cold test (at KEK site)



Fabrication by MELCO (2004)



Assembling by MELCO (2005)



Performance test (vertical test) by IHEP at KEK (2004)

Cooldown test by IHEP at KEK (2005)

Summary

(KEKB-SC)

- Beam intensity of HER reached 1.4 A.
- No beam instability caused by the SC-RF was found.
- SC cavities can provide the voltage of 1.4 MV/cavity and 300 – 350 kW/cavity to the beam of 1.4 A.
- The HOM absorbed by the damper reached 16 kW/cavity.
  → SBP / LBP = 7 kW / 9 kW
- Trip rate at 1.4 A is <0.5/day for 8 SC cavities, and <0.1/day at 850mA.
- Need a study to find a simple way to recover the degraded Q.

(IHEP-SC)

- The 500 MHz SC modules based on the KEKB cavity have been completed and commissioned since the end of 2006.
- In the SR mode, the beam intensity has already achieved the design value of 250 mA.
- Roll in of the detector is coming soon.