High Average Current Superconducting RF Cavities

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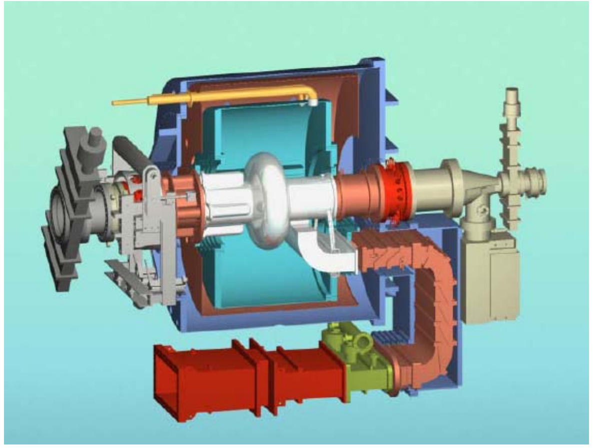
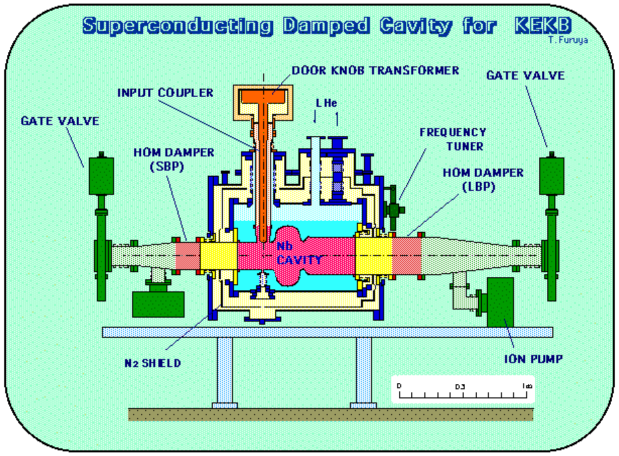
SC for Factories

◆SC application to high current storage rings

- In the 1990s, precise experiments supported by "factory machines" based on a storage ring were proposed, B-factory.
- Ampere class beams of electron and positron collide with each other.
- To storage such a high current beam distributed in many bunches, an RF system with a sufficiently damped HOM was required to avoid multi bunch instabilities.
- For this requirement, single-cell HOM-free SC cavities were developed at Cornell & KEK for their B-factory colliders.



500 MHz CESR-B cavity



509 MHz KEKB cavity

SC for Factories

- **Advantage of SC for I A beam : sufficiently damped HOMs**

CW operation at high accelerating gradient

→ reduction of the total number of cavities
→ Typical gradient of 10 MV/m, in compare with 1 - 2 MV/m of NC.
→ reduction of the total HOM impedance of the ring.
→ single cell cavity → low impedance of HOMs
→ to reduce a coupler power

Simple HOM damping scheme using beam line dampers

→ The cavity shape with a large beam aperture is possible.
→ The HOMs can propagate easily out of the cavity through the beam pipes.
→ Rather low R/Q of the accelerating mode

Reduce the amount of the frequency shift to minimize the input power.
(It is more serious for a large circumference because of the low revolution frequency.)

$$\Delta f_0 = -\frac{I_b f_0}{2V_c}(R/Q)\sin\phi_s < f_{rev}$$

I_b: beam current
f_0: resonant frequency
V_c: cavity voltage
f_{rev}: revolution frequency

Suppress the RF phase oscillation caused by a bunch space.

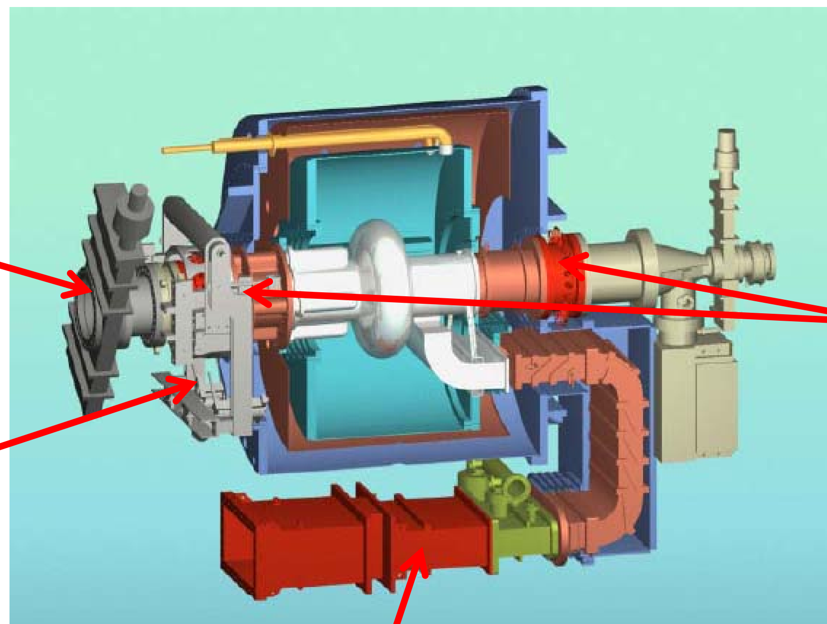
$$\Delta\phi \propto \frac{\pi f_0}{V_c}\left(\frac{R}{Q}\right) I_b T_{gap}$$

T_{gap}: duration of the empty buckets

SC for Factories

◆ **cavity module: CESR-B cavity (Cornell)**

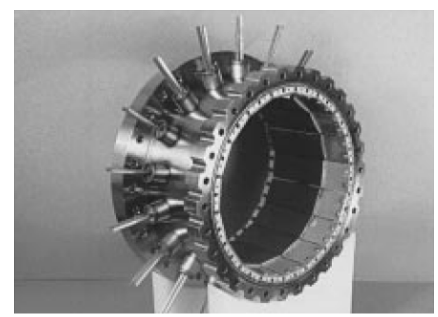
500 MHz single cell cavity
- Iris dia. of 240 mm
- fluted beam pipe
- R/Q = 88 ohm
- Esp/Eacc=2.5
- BCPed



Gate valve

Frequency tuner

Ferrite damper



RF window
Wave guide coupler
- max 280 kW

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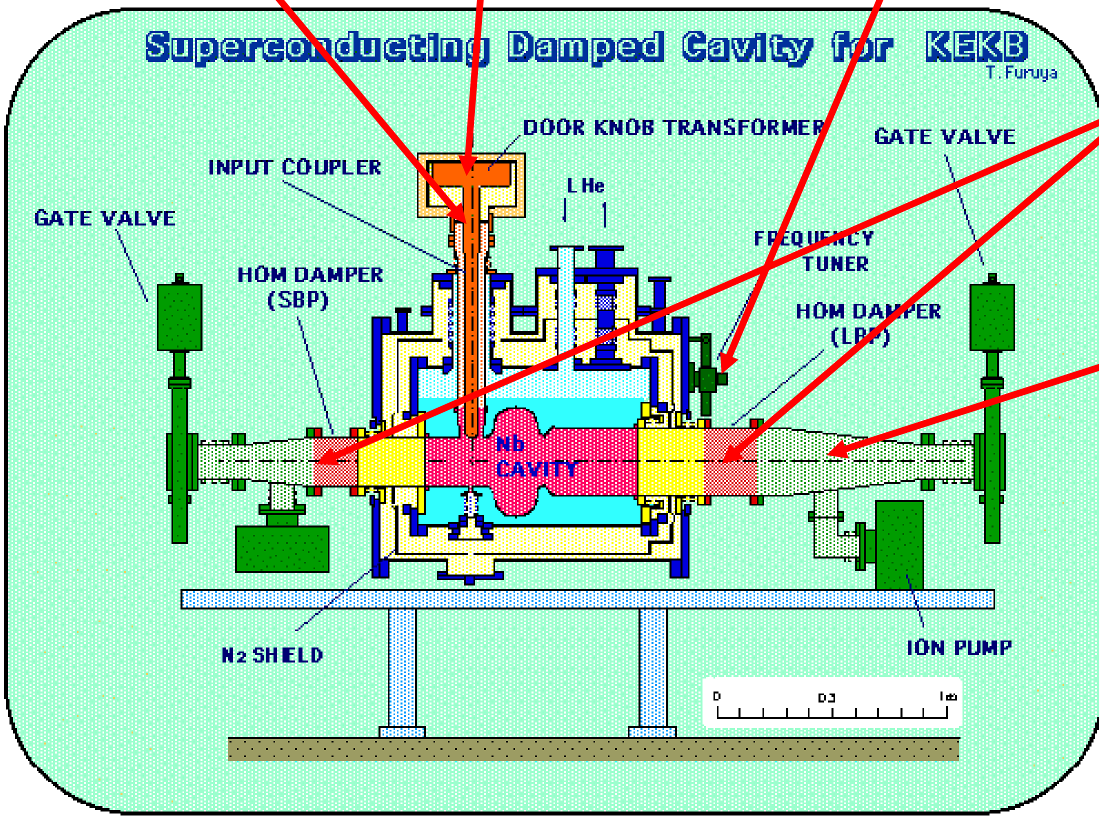
◆ cavity module: KEKB (KEK)

Coaxial ceramic disk

Doorknob
- bias voltage(±2kV)

Frequency tuner
- motor (coarse)
- piezo (fine)



Cylindrical ferrite damper
- 4 mm in thick

Long taper
- to reduce a loss factor
- 60 cm

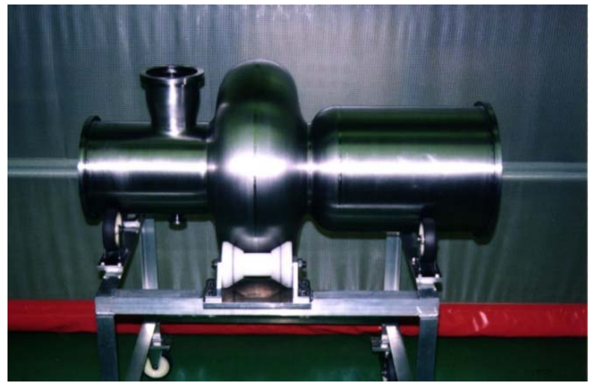
509 MHz single cell cavity

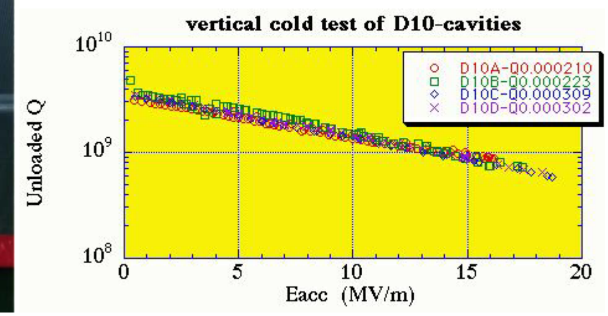
Number of cavity: 8
Accelerating gap: 0.243 m
R/Q: 93 ohm
Length of the module: 3.7 m
Beam hight: 1500 mm
Total hight: 3000 mm
(not including TR Tube)
Operating temperature: 4.4K

SC for Factories

◆ key components

Cavity
- Nb single-cell
- Frequency: 509 MHz
- Gap length: 0.243 m
- R/Q : 93 Ohm
- electropolised
- annealed at 700C

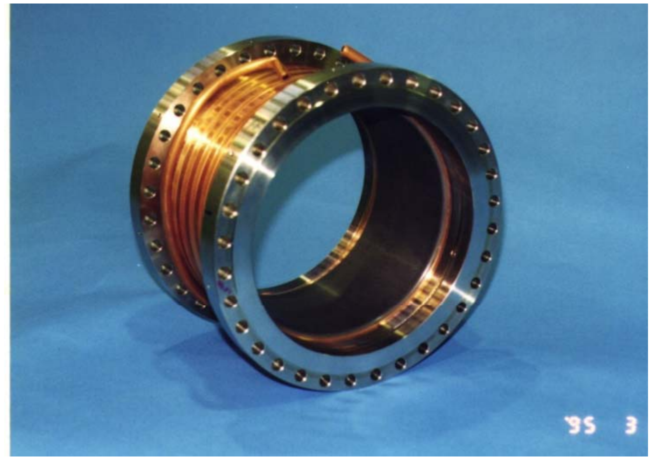




Input Couplers
- Handling power of 400 kW(CW)
- Full reflection of 300 kW(CW)
- Qext = 5 x 10^4
- Ceramic disk of 152dia.
- Water cooling of inner and He gas cooling of outer conductor
- DC bias voltage to 2 kV between inner and outer conductors for conditioning.
- monitor & protection

SC for Factories

HOM Absorbers
- IB004 Ferrite of 4mm in thickness
- HIP (950℃×1500atm)
- located at RT side
- water cooling
- size
  - 300dia x 150 mm for LBP
  - 220dia x 120 mm for SBP



Loss factor of short bunch length

Strongly depend on the bunch length

More than 25 GHz for 4mm bunch

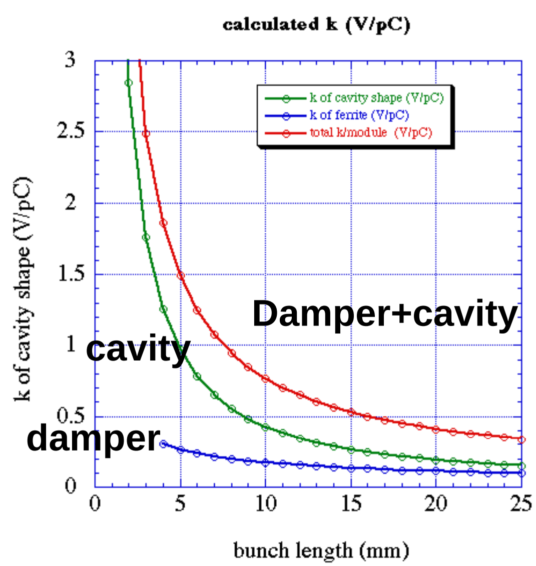
Power is

$$P = k(\sigma_z) \cdot q \cdot I_0$$

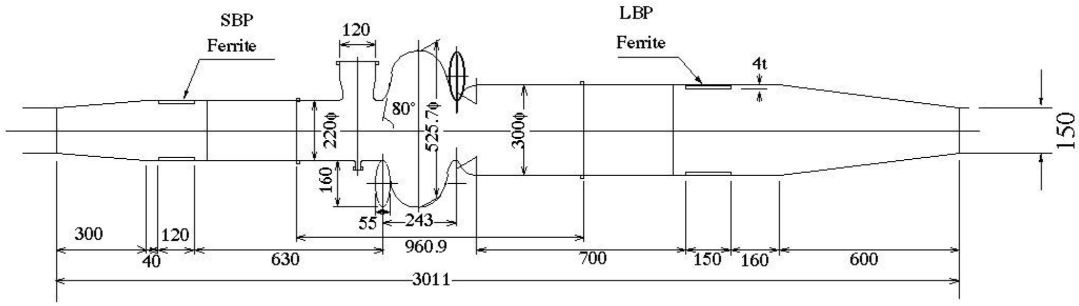
k: loss factor

q: bunch charge

I_0: average current



HOM damping: optimization of ferrite dampers

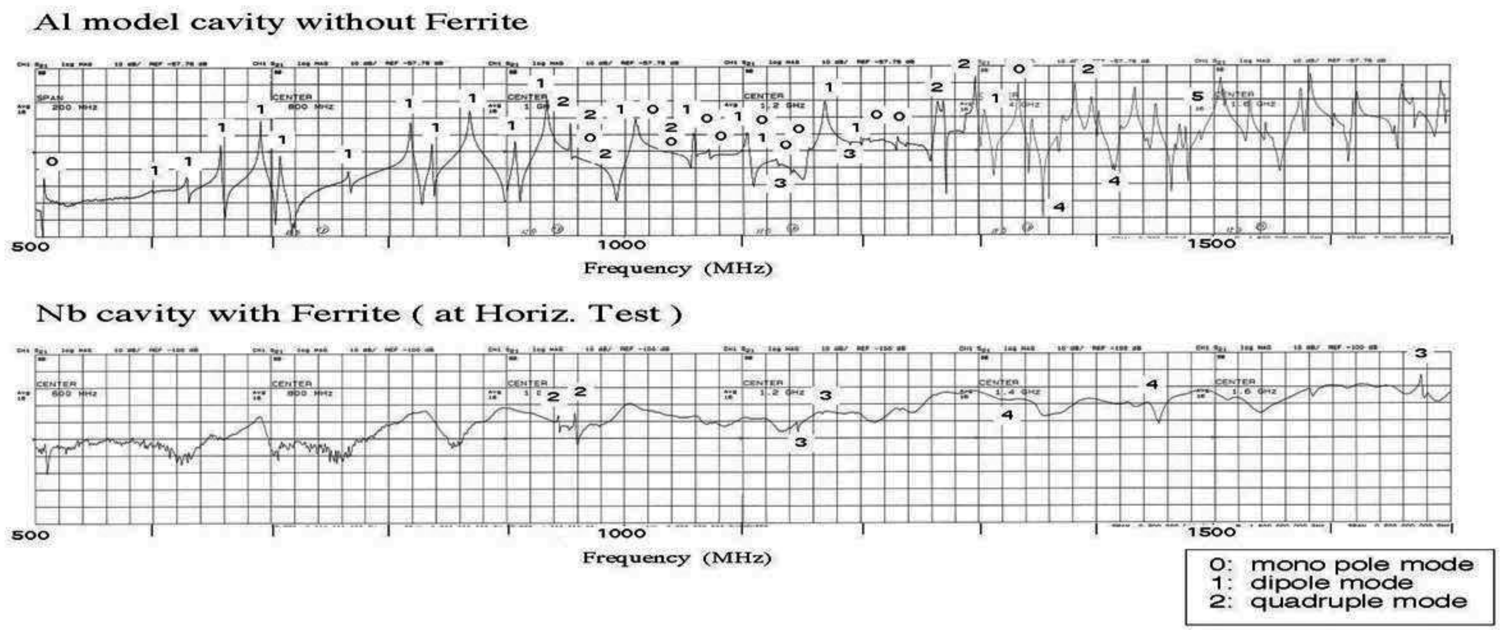


Typical HOM

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



SC for Factories

◆ Operation: KEKB/The strongest e+/e- collider

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

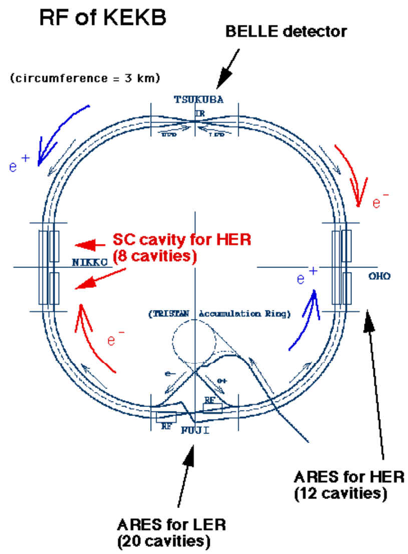
Physics run of 8 years since 1999.

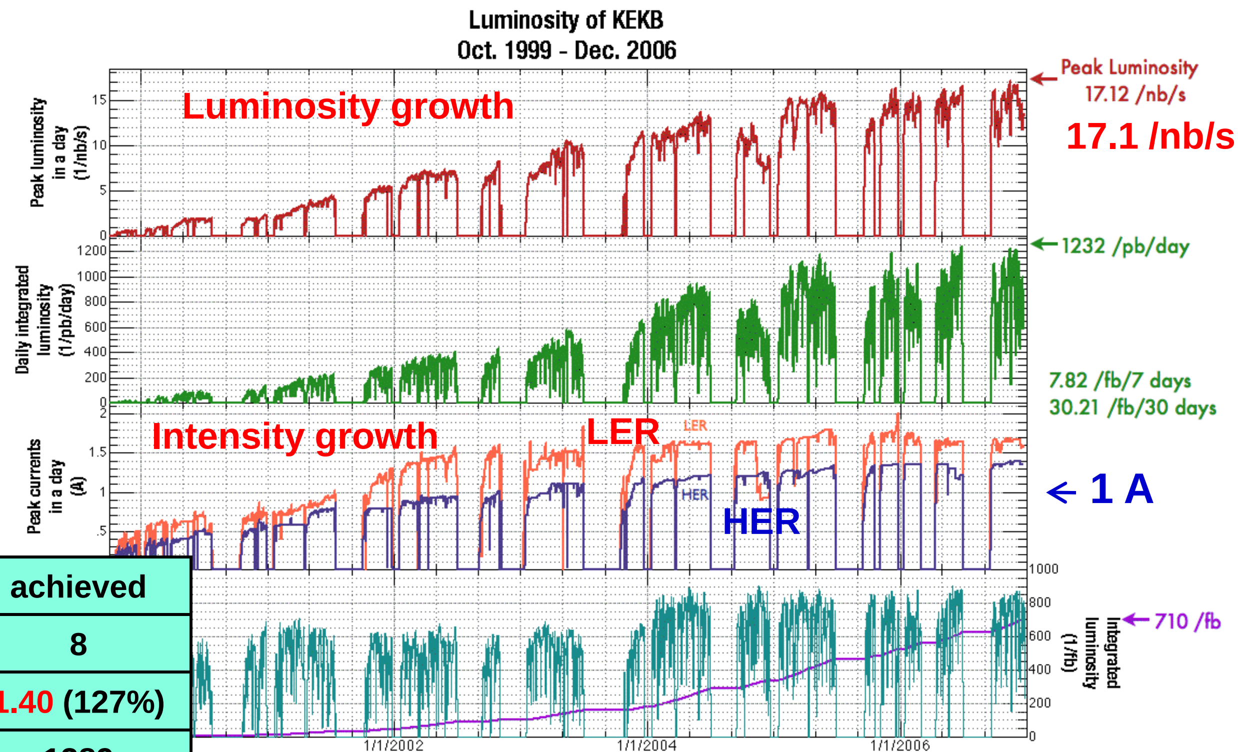
Accumulated luminosity of 760 fb^{-1} with the peak luminosity of 1.7×10^{34} $cm^{-2}s^{-1}$.

Design Parameters

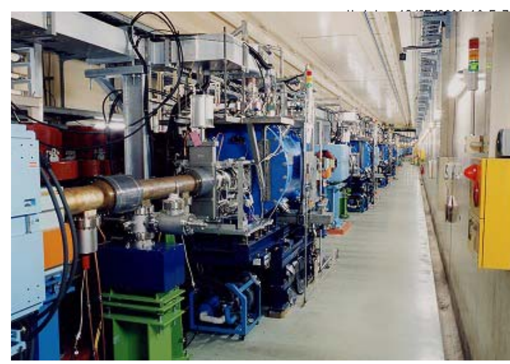
	e+/LER	e-/HER
beam energy	3.5 GeV	8 GeV
beam current	2.6 A	1.1 A
harmonic no.	5120	
bunch space	0.6 m	0.6 m
bunch charge	5.2 nC	2.2 nC
horiz. emittance	18 nm	18 nm
(βx,βy) at IP	(33cm, 1cm)	
crossing angle	11 mrad	11 mrad
peak luminosity	1×10^{34} $cm^{-2}s^{-1}$	
luminosity /day	600 pb^{-1}	
circumference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

SC for Factories





	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



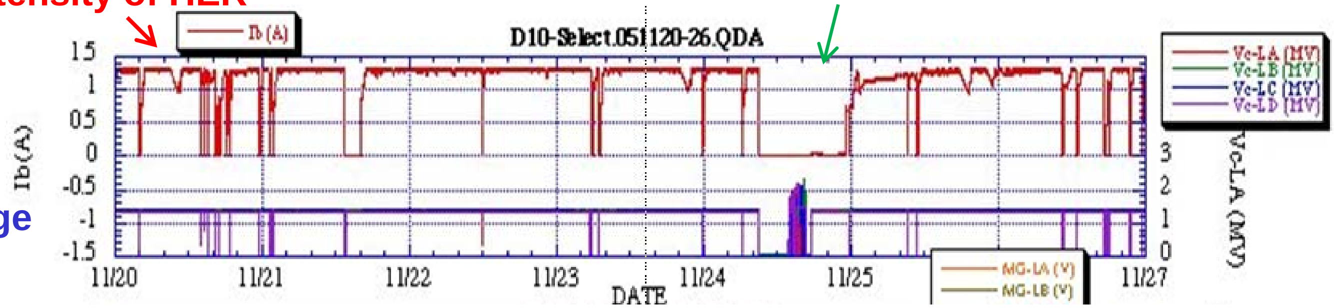
SC for Factories

◆Top-up operation

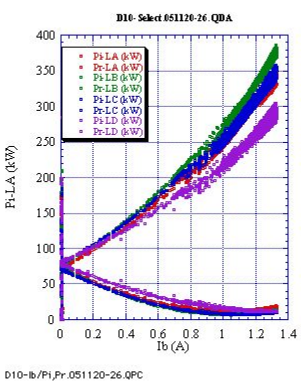
Beam intensity of HER

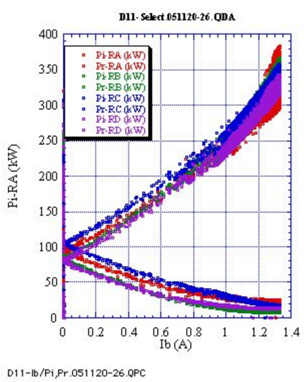
Machine maintenance

Cavity voltage



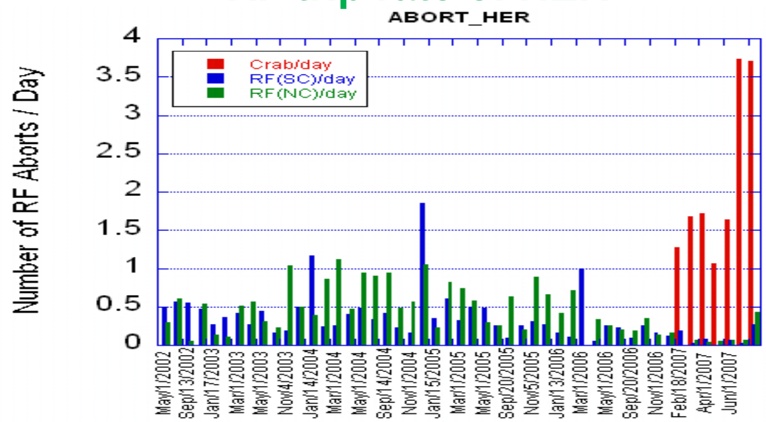
Input & reflection power





- small reflection at top-up
- delivering power of 2.6 MW

RF trip rate of HER



- trip rate of HER (NC(gn), SC(bl), CRAB(rd))
- SC: 0.5/day at 1.4A, and 0.1/day at 0.85A.

SC for Factories

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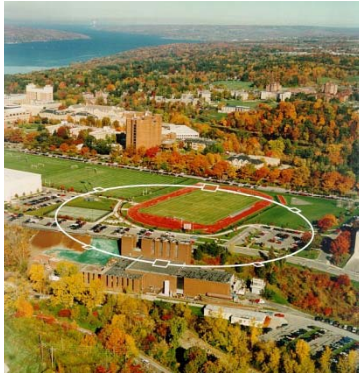
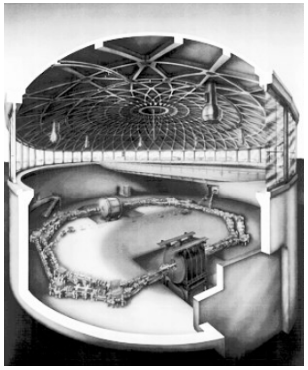
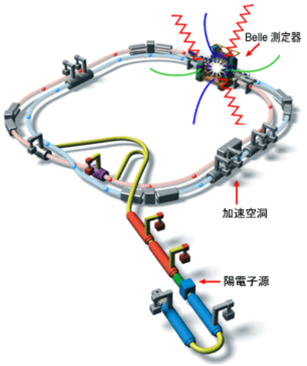
- The first HOM free SC cavity was commissioned at Cornell in 1997.
- BEPC-II cavity is a modified KEKB cavity to change the frequency to 500MHz.
- Single cell HOM-free cavities provided stable operation of 1.4 A .

	CESR e + e-	DAΦNE e + e-	PEP-II e + e-	KEKB e + e-	BEPC-II e + e-	VEPP2000 e + e-
physics	B	Φ	B	B	τ-c	Φ
energy (GeV)	5.3 - 5.3	0.51 - 0.51	3.1 - 9.0	3.5 - 8.0	1.5 - 1.5	1.0 - 1.0
Current (A)	0.37 - 0.37	1.4 - 2.0	2.7 - 1.8	1.7 - 1.4	0.9 - 0.9	0.11 - 0.1
RF cavity	500MHz SC(4)	368 MHz NC	476 MHz NC	509 MHz NC+SC(8)	500 MHz SC(2)	172 MHz NC
luminosity [$nb^{-1}s^{-1}$]	1.2	0.15	11	17	1	-
commissioning	1979-2007	1998-	1998-2008	1998-	2006-	-







SC for SR light source

◆Application of HOM damped cavities (1): light sources

- Because of successful operation of SC damped cavity in factory machines, this technology became an attractive way to upgrade the storage rings for light source that have a limited RF space.
- The technology of CESR-B cavity was transferred to an industry.
- Soleil cavity is based on the LEP cavity technology, Nb-Cu. HOM modes are damped by beam pipe couplers.

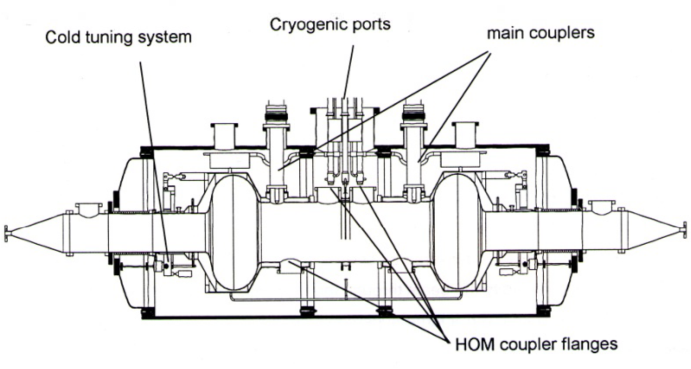
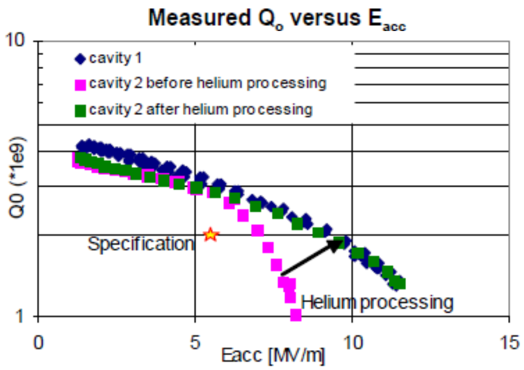


Figure 1 : Schematic view of the cryostat with the two SRF cavities



352 MHz SOLEIL cavity based on the LEP cavity technology, Nb-Cu.

SC for SR light source

◆ Application of HOM damped cavities (1): light source

	CESR	TLS	CLS	Diamond	SSRF	BEPC-II	SOLEIL	NSLS-II	TPS
Energy (GeV)	5.3	1.5	2.5	3.0	3.5	2.5	2.75	3.0	3.0
Current (mA)	500	500	250	300	200	250	500	500	400
frequency (MHz)	500	500	500	500	500	500	352	500	500
Cavity type	CESR	CESR	CESR	CESR	CESR	KEKB	SOLEIL	-	-
Number of cav	4	1	1	2	3	2	4	4	4
Voltage (MV/cav)	1.3	1.6	2.4	2.0	2.0	1.5	1.5	1.7	1.2
Power/coupler(kW)	160	82	245	270	250	96	150	225	180





Big Bang machine; "LHC"

◆ **Application of HOM damped cavities (2) : LHC**

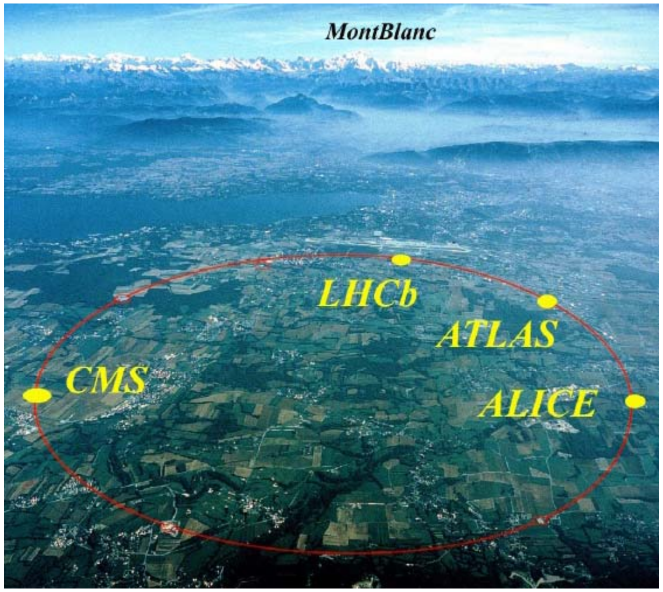
Big Bang machine uses 16 SC cavities for the proton beams of 0.58 A x 2.

→A wide beam aperture of 30 cm is available.

→Suppress the RF phase oscillation due to a long bunch gap of 3 μs.

→Less number of cavities and strong HOM damping reduce the total HOM impedance.

Beam energy	**0.45 → 7 TeV**
Bunch charge	**18 nC**
Bunch space	**30 m**
Average current	**0.58 A**
Bunch length (4σ)	**1.7 → 1.1 ns**
Accelerating voltage	**16 MV (5.5 MV/m)**
RF frequency	**400 MHz**
Number of cavities	**8 /beam**
RF power at ramping	**275 kW/cavity**
klystron	**300 kW x 16**

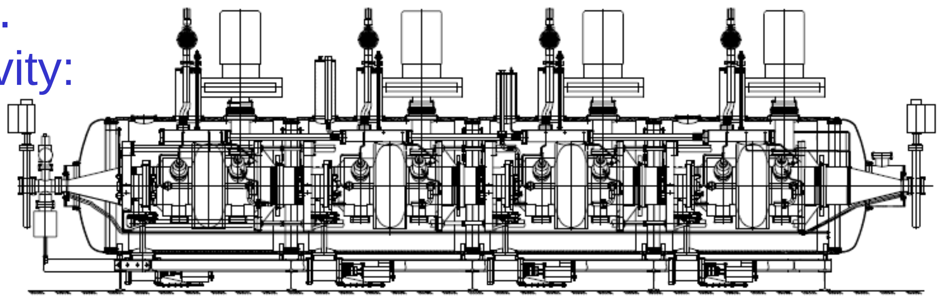


Big Bang machine; "LHC"

◆ LHC SC cavity module

Two modules per beam.
Each module contains 4 SC cavities.
Cavity technology based on LEP cavity:

→ Nb-Cu cavity
→ beam pipe HOM coupler
→ variable input coupler



Cavity type	**Nb-Cu, single-cell**
frequency	**400 MHz**
R/Q (V^2/P)	**90 ohm**
Power coupler	**Coax-type (variable)**
Accelerating voltage	**16 MV (5.5 MV/m)**
Number of cavities	**8**
R/Q (V^2/P)	**90 ohm**
HOM damping	**4 couplers for each**

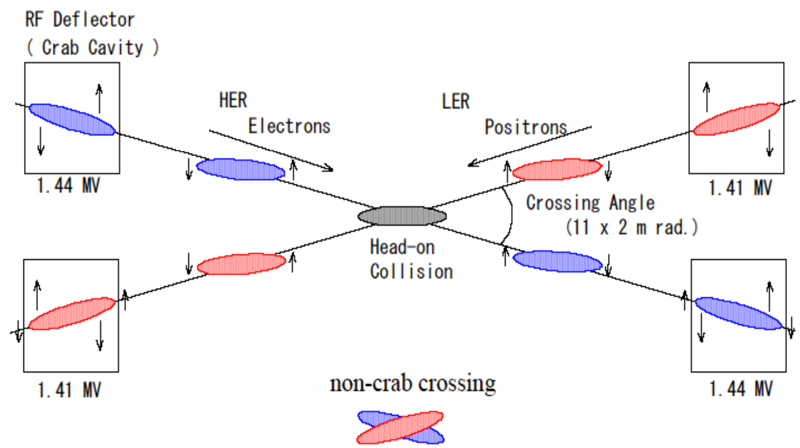
The 400 MHz cavity. Four cells installed in their cryostat.

Beam deflection: CRAB cavity

◆Application of HOM damped cavities (3): beam deflection

- KEKB collides the e+ and e- with a finite crossing angle of 22 mrad to obtain the minimum bunch spacing of 0.6 m, avoiding the first parasitic collision.
- Crab crossing scheme makes a head-on collision in the finite crossing scheme so as to suppress the beam-beam interaction.
- Recent simulation study of crab crossing showed the possibility of luminosity enhancement not only by geometrical effect but also by a beam-beam effect on the beam size.
- Kick voltage is determined by the beta function and the phase advance of betatron oscillation at the cavity location, typically 0.9 – 1.4 MV.
- Two crab cavities were installed and commissioned.

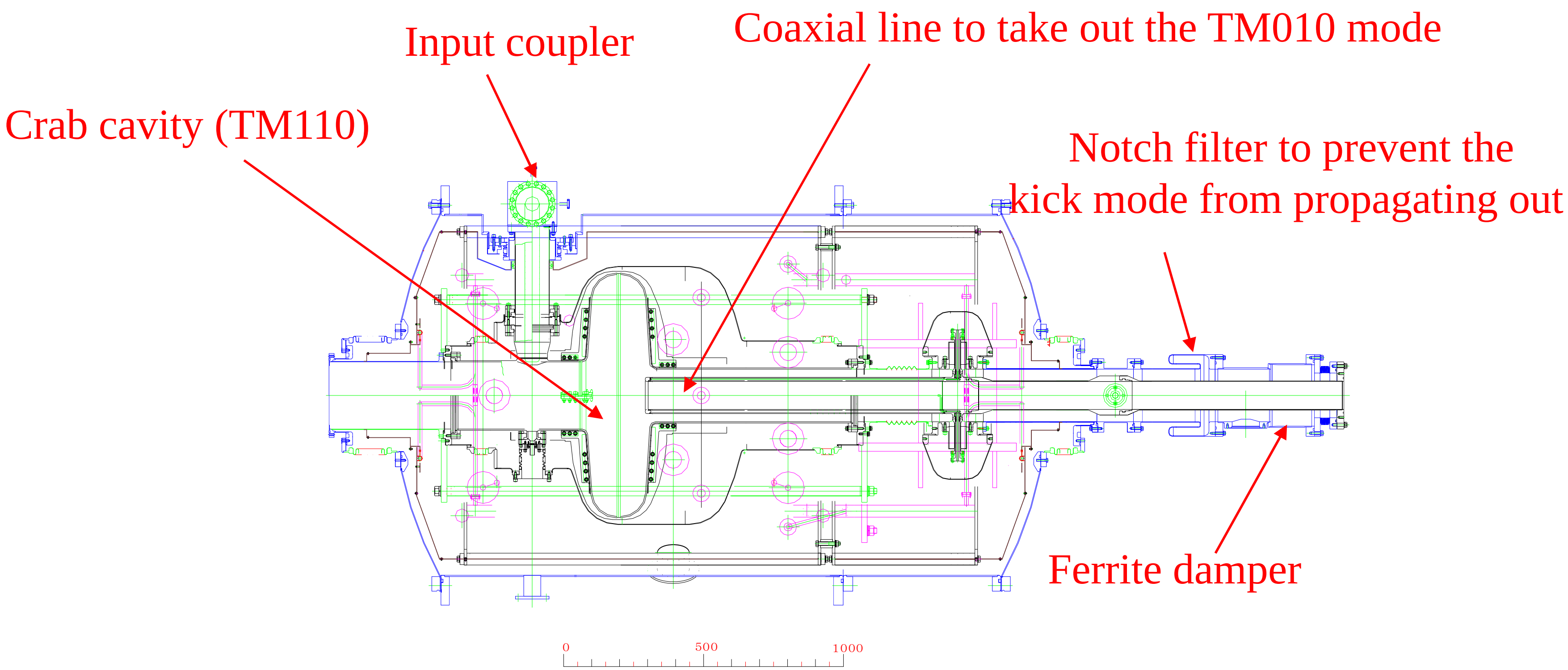
Frequencyfor	508.887MHz
R/Q	46.7 ohm
Esp/Vkick	14.4MV/m/MV
Hsp/Vkick	415 Oe/MV
Kick voltage	1.44 MV



Beam deflection: CRAB cavity

◆Structure of a CRAB module

- The beam bunches are kicked in the horizontal by TM110 which is not the lowest mode of the cavity.
- The lowest mode, TM010 is coupled out by a coaxial line of the beam pipe, and absorbed by a ferrite at the end of the line.



Beam deflection: CRAB cavity

◆Structure of a CRAB module

Ferrite damper

Crab cavity & jacket

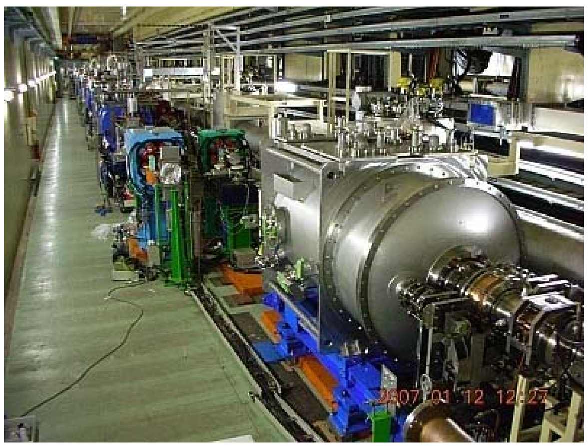
Horizontal test

coaxial line

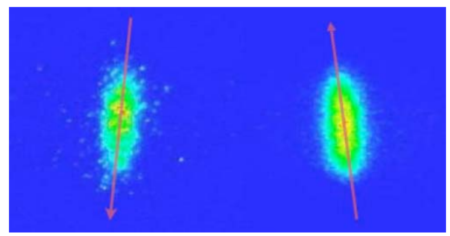
Beam deflection: CRAB cavity

◆ commissioning

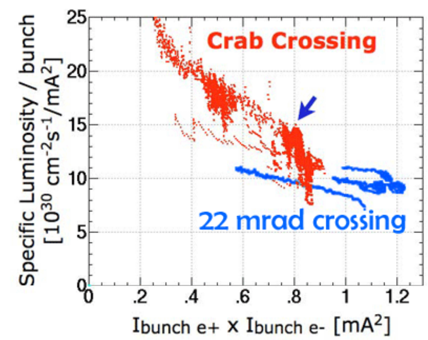
- The cavities were installed in2007.
- The crab kick was confirmed by a streak camera.
- The effect to the luminosity was observed at a low current region, but not at a high current region.



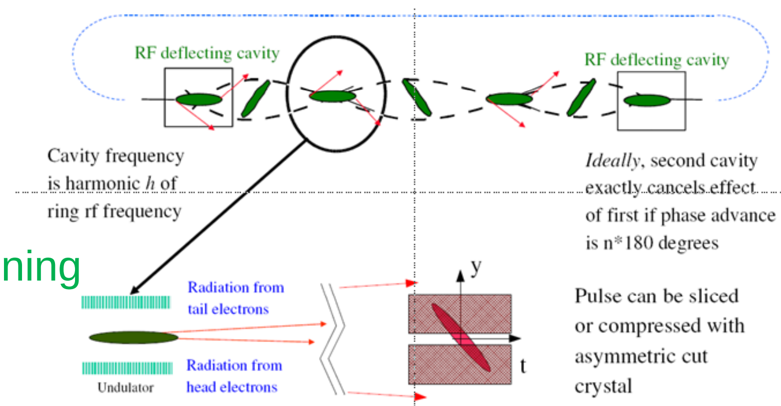
Crab cavity in the KEKB tunnel



Crab effect monitored by streak camera



- The crab cavities worked well, providing a stable kick voltage.
- Crab technology has the possibility of obtaining sub-pico second X-ray pulses by tilting the long bunches using a vertical crab kick.



Multi cell SC for high current: "ERL"

◆ **For an advanced light source:**

ERL is not restricted to the equilibrium longitudinal and transverse emittances of storage rings.

→ Short bunch length and a flexible bunch pattern are available.
→ Electron beam characteristics are determined by the injector.
→ high efficiency, and reduced dump activation.

- experimental demonstration of energy recovering has been done.
  SCA-FEL : using a 50 MeV beam, 1986
  J-Lab FEL: 150 MeV x 10 mA, 1994
  JAERI-FEL; 15 MeV x 10 mA

- another application of ERL: BNL-ERL
  RHIC : electron cooling of gold ion beams
  5-cell 703 MHz SC cavity
  500 mA (1-turn) & 1 A (2-turns)
  eRHIC: electron hadron/heavy ion collider using an ERL
  5-cell 703 MHz SC cavity
  10-25 GeV ERL

Multi cell SC for high current : "ERL"

◆ SC for ERL

two types of SC CW linac:

injector linac:

without energy recovery: 10MV x 100mA = 1 MW

accelerate a beam of 100 mA → heavy beam loading of cw → power coupler

number of cells is determined by the coupler power.

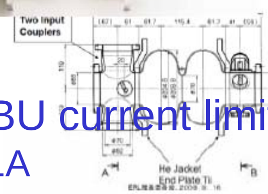
+ injection linac module

→Fabricated a 2-cell prototype cavity.
→Just start the design of CPL and cryo-module.

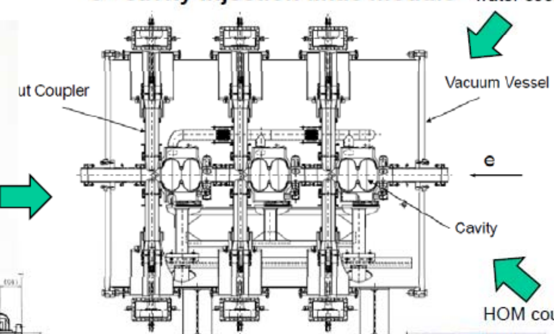
water cooled coupler

Double coupler with water cooling

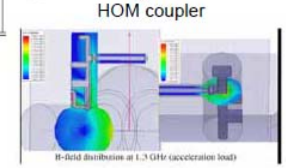
prototype 2-cell cavity



3 –cavity injection linac module



HOM coupler



main linac:

with energy recovery :

high CW gradient of 15 -20 MV/m :

high Q & no field emission

multi cell cavity with damped HOM : BBU current limitation

JLab design: 748 MHz, 5-cell cavity for 1A

BNL design: 703 MHz, 5-cell cavity for 1A

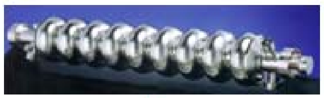
Multi cell SC for high current : “ERL”

- 1.3 GHz, 9-cell structure for 1 A
  - Simulation results

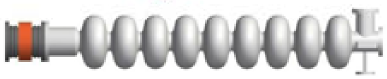
Accelerating mode

Frequency	1300 MHz	Q0×Rs	289 Ohm
gradient	15 - 20 MV/m	Coupling	3.8%
Q0	1 E+10	Esp/Eacc	3.0
R/Q	897 Ohm	Hsp/Eacc	42.5 Oe/(MV/m)

TESLA cavity

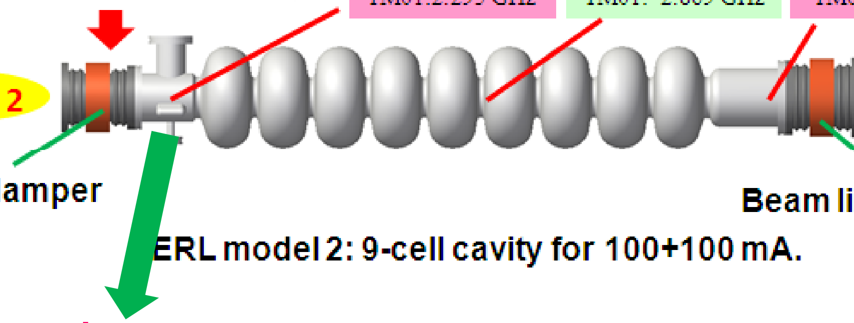


Model 1



SBP dia.：f100	Iris dia.：f80	LBP dia.：f120
TE11: 1.757 GHz	TE11: 2.196 GHz	TE11: 1.464 GHz
TM01:2.295 GHz	TM01: 2.869 GHz	TM01:1.913 GHz

Model 2

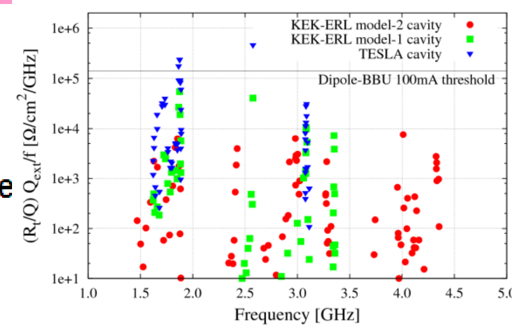


Beam line damper

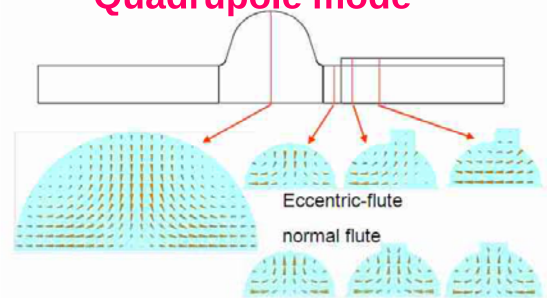
Beam line dampe

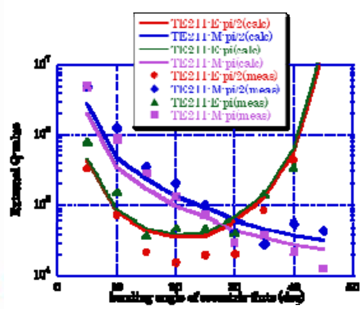
ERL model 2: 9-cell cavity for 100+100 mA.

Dipole mode

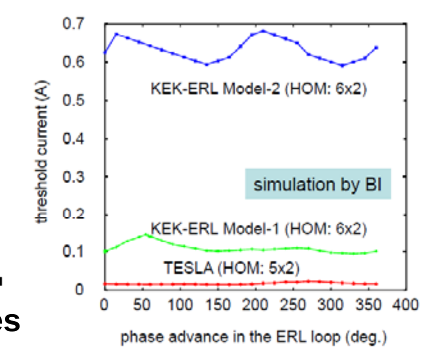


Quadrupole mode

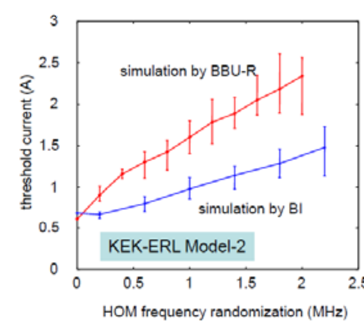




Damping of Q-modes



BBU limt of 600 mA



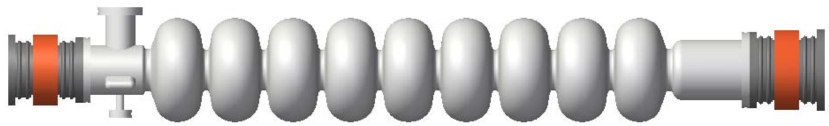
1 A by HOM randomizing

Multi cell SC for high current : "ERL"

◆ 1.3 GHz, 9-cell structure for 1 A

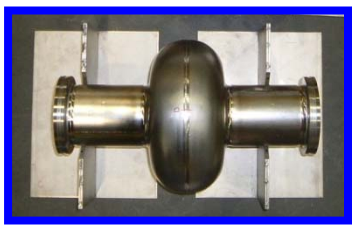
• Vertical test results of prototype cavities

Model 2

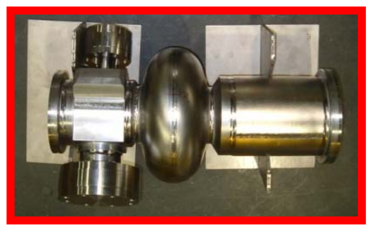


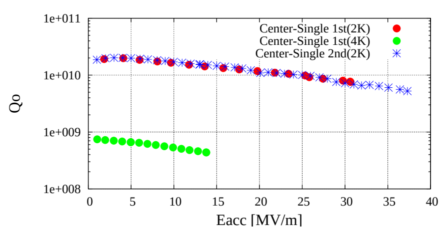
9-cell cavity

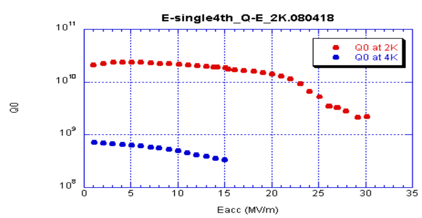
Center-single

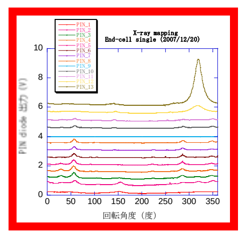


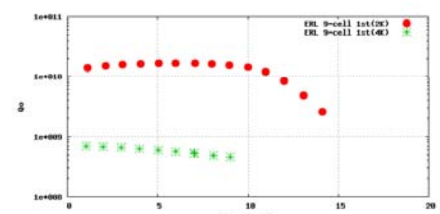
End-single











Emax of >37MV/m
>20 MV/m with 1E+10

Emax of 30 MV/m
>20 MV/m with 1E+10

Meas. on '08/09/17-19
>10 MV/m with 1E+10

Summary

◆ SC for high intensity beam

- Single cell HOM damped cavities have achieved a beam of >1 A in factory machines, delivering a power of 400 kW to the beam.
- Input couplers and HOM dampers (couplers) work well and support the stable operation.
- Application of high current SC cavities is expanded increasingly.
  - to middle size rings of light sources.
  - to deflecting cavity, CRAB
  - to proton rings, LHC.
- New 9 cell shape is optimized as a main linac structure of ERL, which has large diameters of cell iris and beam pipes. Furthermore, mode converter is attached on a beam pipe to propagate out the quadrupole modes.
- BBU simulation shows the threshold limit of ~600 mA for this 9 cell structure.