High Average Current
Superconducting RF Cavities

LINAC2008, Victoria, Canada
2008/10/01

Takaaki Furuya
KEK, Japan
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 store 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
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.)

\[
\Delta f_0 = -\frac{I_b f_0}{2V_c} \left(\frac{R}{Q}\right) \sin \phi_s < f_{rev}
\]

\( I_b \): 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
◆ 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
RF window
Wave guide coupler
• max 280 kW
cavity module: KEKB (KEK)

- Coaxial ceramic disk
  - bias voltage (±2kV)
- 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 height: 1500 mm
Total height: 3000 mm
(not including TR Tube)
Operating temperature: 4.4K
key components

Cavity
- Nb single-cell
- Frequency: 509 MHz
- Gap length: 0.243 m
- R/Q : 93 Ohm
- electropolished
- 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
**HOM Absorbers**
- IB004 Ferrite of 4mm in thickness
- HIP (950°C × 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

**Mode measurements**

<table>
<thead>
<tr>
<th>Mode</th>
<th>Freq. (MHz)</th>
<th>R/Q (ohm)</th>
<th>Q meas.</th>
</tr>
</thead>
<tbody>
<tr>
<td>TM011</td>
<td>1018</td>
<td>7</td>
<td>106</td>
</tr>
<tr>
<td>TM020</td>
<td>1027</td>
<td>6</td>
<td>95</td>
</tr>
<tr>
<td>TE111</td>
<td>688</td>
<td>6*</td>
<td>145</td>
</tr>
<tr>
<td>TM110</td>
<td>705</td>
<td>8*</td>
<td>94</td>
</tr>
</tbody>
</table>

* : R/Q at 5 cm
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 $1.7 \times 10^{34}$ cm⁻²s⁻¹.

### Design Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>e+/LER</th>
<th>e-/HER</th>
</tr>
</thead>
<tbody>
<tr>
<td>beam energy</td>
<td>3.5 GeV</td>
<td>8 GeV</td>
</tr>
<tr>
<td>beam current</td>
<td>2.6 A</td>
<td>1.1 A</td>
</tr>
<tr>
<td>harmonic no.</td>
<td>5120</td>
<td></td>
</tr>
<tr>
<td>bunch space</td>
<td>0.6 m</td>
<td>0.6 m</td>
</tr>
<tr>
<td>bunch charge</td>
<td>5.2 nC</td>
<td>2.2 nC</td>
</tr>
<tr>
<td>horiz. emittance</td>
<td>18 nm</td>
<td>18 nm</td>
</tr>
<tr>
<td>$(\beta_x, \beta_y)$ at IP</td>
<td>(33cm, 1cm)</td>
<td></td>
</tr>
<tr>
<td>crossing angle</td>
<td>11 mrad</td>
<td>11 mrad</td>
</tr>
<tr>
<td>peak luminosity</td>
<td>$1 \times 10^{34}$ cm⁻²s⁻¹</td>
<td></td>
</tr>
<tr>
<td>luminosity /day</td>
<td>600 pb⁻¹</td>
<td></td>
</tr>
<tr>
<td>circumference</td>
<td>3016 m</td>
<td></td>
</tr>
</tbody>
</table>
SC for Factories

LINAC2008
‘08/10/01
T. Furuya

Luminosity growth
17.1/10^{-11}/nb/s

Intensity growth
1232/pb/day
7.82/fb/7 days
30.21/fb/30 days

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Design</th>
<th>Achieved</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of cavities</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Max. beam current (A)</td>
<td>1.1</td>
<td>1.40 (127%)</td>
</tr>
<tr>
<td>No. of bunches</td>
<td>5000</td>
<td>1389</td>
</tr>
<tr>
<td>bunch charge (nC)</td>
<td>2.2</td>
<td>10.1</td>
</tr>
<tr>
<td>Bunch length (mm)</td>
<td>4</td>
<td>6 - 7</td>
</tr>
<tr>
<td>RF voltage (MV/cavity)</td>
<td>1.5</td>
<td>1.2 - 2</td>
</tr>
<tr>
<td>unloaded Q at 2MV</td>
<td>1E+09</td>
<td>0.3 -1E+09</td>
</tr>
<tr>
<td>beam loading (kW/cav)</td>
<td>&gt;250</td>
<td>350 - 400</td>
</tr>
<tr>
<td>HOM loading (kW/cav)</td>
<td>5</td>
<td>14 - 16</td>
</tr>
</tbody>
</table>
◆ Top-up operation

- Beam intensity of HER
- Cavity voltage

Machine maintenance

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**

- 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.

<table>
<thead>
<tr>
<th>physics</th>
<th>CESR e+ e-</th>
<th>DAΦNE e+ e-</th>
<th>PEP-II e+ e-</th>
<th>KEKB e+ e-</th>
<th>BEPC-II e+ e-</th>
<th>VEPP2000 e+ e-</th>
</tr>
</thead>
<tbody>
<tr>
<td>energy (GeV)</td>
<td>5.3 - 5.3</td>
<td>0.51 - 0.51</td>
<td>3.1 - 9.0</td>
<td>3.5 - 8.0</td>
<td>1.5 - 1.5</td>
<td>1.0 - 1.0</td>
</tr>
<tr>
<td>Current (A)</td>
<td>0.37 - 0.37</td>
<td>1.4 - 2.0</td>
<td>2.7 - 1.8</td>
<td>1.7 - 1.4</td>
<td>0.9 - 0.9</td>
<td>0.11 - 0.1</td>
</tr>
<tr>
<td>RF cavity</td>
<td>500MHz SC(4)</td>
<td>368 MHz NC</td>
<td>476 MHz NC</td>
<td>509 MHz NC+SC(8)</td>
<td>500 MHz SC(2)</td>
<td>172 MHz NC</td>
</tr>
<tr>
<td>luminosity [nb⁻¹s⁻¹]</td>
<td>1.2</td>
<td>0.15</td>
<td>11</td>
<td>17</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>
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 sources 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.

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**

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

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

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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>508.887 MHz</td>
</tr>
<tr>
<td>R/Q</td>
<td>46.7 ohm</td>
</tr>
<tr>
<td>Esp/Vkick</td>
<td>14.4 MV/m/MV</td>
</tr>
<tr>
<td>Hsp/Vkick</td>
<td>415 Oe/MV</td>
</tr>
<tr>
<td>Kick voltage</td>
<td>1.44 MV</td>
</tr>
</tbody>
</table>
**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

coaxial line

Horizontal test
Beam deflection: CRAB cavity

**commissioning**

- The cavities were installed in 2007.
- 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.

- 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: $10\text{MV} \times 100\text{mA} = 1\text{MW}$
accelerate a beam of 100 mA $\rightarrow$ heavy beam loading of cw $\rightarrow$ power coupler
number of cells is determined by the coupler power.

+ injection linac module
  $\rightarrow$ Fabricated a 2-cell prototype cavity.
  $\rightarrow$ Just start the design of CPL and cryo-module.

**Double coupler with water cooling**

**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

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

Dipole mode

BBU limit 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 >37 MV/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
**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.