RF Accelerating Cavity for SuperKEKB Damping Ring and its Breakdown Study

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on behalf of SuperKEKB-RF / ARES Cavity group
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This presentation is based on the following papers:

Updated version to be submitted to PRST-AB

HG2015 Workshop at Tsinghua University, Beijing, China
2015-06-19
New Positron Damping Ring (DR) for low-emittance beam injection to SuperKEKB / LER(e⁺)

Parameters of the Damping Ring

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>1.1 GeV</td>
</tr>
<tr>
<td>No. of bunch trains / bunches per train</td>
<td>2 / 2</td>
</tr>
<tr>
<td>Circumference</td>
<td>135.5 m</td>
</tr>
<tr>
<td>Maximum stored current*</td>
<td>70.8 mA</td>
</tr>
<tr>
<td>Energy loss per turn</td>
<td>0.091 MV</td>
</tr>
<tr>
<td>Horizontal damping time</td>
<td>10.9 ms</td>
</tr>
<tr>
<td>Injected-beam emittance</td>
<td>1700 nm</td>
</tr>
<tr>
<td>Equilibrium emittance (h/v)</td>
<td>41.4 / 2.07 nm</td>
</tr>
<tr>
<td>Coupling</td>
<td>5 %</td>
</tr>
<tr>
<td>Emittance at extraction (h/v)</td>
<td>42.5 / 3.15 nm</td>
</tr>
<tr>
<td>Energy band-width of injected beam</td>
<td>± 1.5 %</td>
</tr>
<tr>
<td>Energy spread</td>
<td>0.055 %</td>
</tr>
<tr>
<td>Bunch length</td>
<td>6.5 mm</td>
</tr>
<tr>
<td>Momentum compaction factor</td>
<td>0.0141</td>
</tr>
<tr>
<td>Number of normal cells</td>
<td>32</td>
</tr>
<tr>
<td>Cavity voltage for 1.5% bucket-height</td>
<td>1.4 MV</td>
</tr>
<tr>
<td>RF frequency</td>
<td>509 MHz</td>
</tr>
<tr>
<td>Inner diameter of chamber</td>
<td>32 mm</td>
</tr>
<tr>
<td>Bore diameter of magnets</td>
<td>44 mm</td>
</tr>
</tbody>
</table>

* 8 nC/bunch

MAC10

- 1.0
- 12.7
- 2100
- 14 / 1.4
- 10
- 17.6 / 5.1

- 5.4
- 0.0019

RF section

e+ DR

(Shown by M. Kikuchi at KEKB Review 2011)

- Construction of the tunnel and facility finished
- Installation of magnets and vacuum chambers this year
- Installation of RF cavities next year

Injector Linac

2015-06-19

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DR Facility on the Ground

Building facade

(Photos taken on 2015-06-12)

Space for the 1MW CW klystron

Inside the building

Local control room
In the DR Tunnel

- Space for the RF cavities
- Magnets of the Beam Transport Line

(Photos taken on 2015-06-12)
NC RF Accelerating Structure for the DR

The blue, gray, green, and magenta regions indicate the vacuum, HOM absorbers, coaxial lines of input couplers, and plungers of movable tuners, respectively. The colored arrows indicate the direction of the positron beam.

- RF operation frequency: 508.9MHz
  - Same as that of the MRs
- Based on the HOM-damped structure of the successful ARES cavity system
- Three cavities at max. to be installed in a space originally designed for one cavity (~3m in the beam direction)
  - Total $V_c = 2.4$MV at max.
- Apart from the CC and SC of ARES, this DR cavity has the following space saving features that are not included in the ARES:
  - The HOM absorbers are all compact tile-shaped SiC ceramics
  - The neighboring cavities share a GBP in-between
  - The cavity is connected directly to GBPs with lip welding for vacuum sealing at the outer periphery (“weld ring gasket”)
- “Multi Single Cell” structure
  - Coupling of the Accel. mode and HOMs among the cavities significantly suppressed by the HOM dampers on the GBPs
  - One big mechanical structure with solid connections of the components
- Loss factor of this structure: 2.3 V/pC (bunch length: 6.0mm)
- Vacuum pumps directly attached to each cavity
- In the DR tunnel, we will assemble the cavities separating them with GBPs similar to LEGO blocks.
Two Types of HOM Damped Structures

Proven by the long-term successful operation at KEKB

HOM waveguides for damping:
- Monopole HOMs
- Vertically-polarized dipole modes

Grooved Beam Pipe (GBP) for damping:
- Horizontally-polarized dipole modes


We can use the horizontal space for
- Movable tuner
- RF-power input, and
- Vacuum evacuation
RF Cavity for the DR (DR Cavity)

Rectangular flange connected to a HOM waveguide load

**UHF CW Single-Cell NC Cavity**

- RF operation frequency: 508.9 MHz
- \( R_{sh}/Q_0 \): 150 \( \Omega \)
- \( Q_0 \): \( \approx 30000 \) (97\% IACS)
- Gradient required in operation:
  - \( V_c = 0.7 \) MV
  - \( E_{acc} = 2.7 \) MV/m
- Gradient in specification:
  - \( V_c = 0.8 \) MV
  - \( E_{acc} = 3.1 \) MV/m
- Wall-loss power at \( V_c = 0.7 \) MV: \( \approx 110 \) kW
- Wall-loss power at \( V_c = 0.8 \) MV: \( \approx 140 \) kW

- Made of OFC (class1)
- Gap length: 256 mm
- \( E_{surf}/E_{acc} = 3.8 \) (max)

\( E_{surf} < \sim 13 \) MV/m
No difference between No.1 and No.2 in the:

- Electric design
- Mechanical structure, and
- Fabrication method
The Endplates of DR Cavity No.1 and No.2 were Electro-Polished (EP).

Material: OFC (class1), 40\,\mu m etching, Skin depth(\delta)@500MHz: 3\,\mu m

**Before EP**
\[ R_a = 1.5\,\mu m, \ R_y = 8\,\mu m \]

**After EP**
\[ R_a = 0.2\,\mu m, \ R_y = 1\,\mu m \quad ( < \delta = 3\,\mu m) \]
Low-Power Measurements of Unloaded Q-factor ($Q_0$)

### Q0(meas) / Q0(sim)

<table>
<thead>
<tr>
<th></th>
<th>Q0(meas) / Q0(sim)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prototype</td>
<td>92.9%IACS</td>
</tr>
<tr>
<td>Cavity No.1</td>
<td>97.1%IACS</td>
</tr>
<tr>
<td>Cavity No.2</td>
<td>97.3%IACS</td>
</tr>
</tbody>
</table>

4% improvement with EP

(Note: No EP applied to the barrel)
Breakdown Study based on Direct In-Situ Observation of Inner Surfaces of the DR Cavity No.2

which has the following 3 characteristics:

1. **Exhaustive** observation
   - To capture all of cavity breakdowns

2. **Multi-directional** and **wide-field** observation
   - To witness the origin of the cavity breakdown

3. **Quantitative** data analyses
   - What is majority and significant?
Setup of High-Gradient (HG) Test

Toshiba CW Klystron E3732 (1MW, 508.9 MHz)
3 TV cameras for **Multi-directional and wide-field observation**
Mirror Chamber

(a) ICF203 Blank Flange with the Mirror
(b) Mirror (Al)
(c) Mirror Chamber 1
TV Camera 2
TV Camera

**Image Sensor**: 1/3-inch CCD

**Minimum illuminance of object**: 0.05 lux (color)

**S/N**: > 52 dB

**Gross Sensor Resolution**: 52x10^4 pixels

**Output format**: NTSC

**Frame rate**: 30 fps

**Price**: About 20,000 YEN
Skip Back Recorder

- OS: Linux
- Input video: NTSC
- Trigger: RF switch “ON → OFF”

All of the cavity-breakdown events recorded automatically (5 seconds before, until 1 second after this trigger)

Exhaustive observation
Identification of Cavity Breakdown by the Decay Time in Pickup Signal

1. Interlock system works with a reflection level over the threshold
2. Check the decay time of the pickup signal
   - ~8 μs → Not cavity breakdown
   - << 8 μs → Cavity breakdown

FIG. 6: Waveforms of the oscilloscope displayed with a time span of 20 μs (2 μs/div). The red dashed curves indicate the envelope of the 508.9 MHz pickup signal from DR Cavity No.2, and the red solid lines indicate its zero amplitude. (a) When the RF switch was turned off due to a reason related to the klystron. (b) Example of the cavity-breakdown events.
RF-Conditioning Histories

- 83 hours to reach 0.90MV/cav
- 95 hours to reach 0.90MV/cav
- 107 hours to reach 0.95MV/cav

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.

- $P_{in}$ ($P_{ref}$): input power to (reflected power from) the cavity
- Wall-loss power: $P_{wall} = P_{in} - P_{ref} = \sim 0.99 \times P_{in}$
- Cavity No.2 reached 0.95MV/cavity successfully.
- Comparable conditioning speeds btwn Cavity No. 1 and 2
After the RF Conditioning completed, Stability Test with Keeping $V_c = 0.90$ MV/cav

- Cavity No.1: 3 breakdowns for 14.5 hours in total = $5.0^{+4.8}_{-2.7}/24$ hrs
- Cavity No.2: 11 breakdowns for 80 hours in total = $3.3^{+1.3}_{-1.0}/24$ hrs

Example of the daily histories

$V_c = 0.70$ MV/cav (required for DR operation)

Same stability between DR Cavity No. 1 and 2 within the statistics
Radiation Dose Rate

Indirect observation of the dark current:

- Field emission
- Acceleration
- Impact on the inner surface
- Emission of X-ray

No significant difference between DR Cavity No. 1 and No. 2

Constant during the stability test (20 cavity breakdowns in this period)

$V_c = 0.90 \text{ MV}$ for DR Cavity No. 2

$\text{Radiation Dose Rate \ [\mu Sv/h]}$ vs $V_c \ [\text{MV}]$
No significant difference between DR Cavity No.1 and No.2 found in:

- $Q_0$
- Conditioning speed
- Vacuum performance
- HG performance, including BDR
- Radiation dose rate (dark current)

No cavity’s particular problems or characteristics found

We can perform breakdown study only for DR Cavity No.2 without loss of generality.
Statistical Data Analysis of Cavity Breakdown Events for DR Cavity No.2
Example of the Recorded Videos

- By TV camera 3
- During operation with $V_c = 0.90$ MV ($E_{acc} = 3.5$ MV/m)
- Non-breakdown status

Clear bright spots observed on the endplates during the RF operation

- Keeping their intensity
- Giving no significant effects on the RF operation as long as the intensity remaining stable
Surface field on the Endplates

Scaled for $V_c=0.90$ MV
($E_{acc}=3.5$ MV/m)

Accelerating mode: $\text{TM}_{010}$

E-field for $0.9$ MV (peak)
- Component: Abs
- Orientation: Outside
- 3D Maximum [V/m]: $13.28 \times 10^6$
- Frequency: $0.5030146$
- Phase: $0$

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Example of Cavity-Breakdown Events (1)

Flash!

$T < 0$

$T = 0$

Cavity Breakdown!

at $V_c = 0.76$ MV ($E_{acc} = 3.0$ MV/m)
Example of Cavity-Breakdown Events (2)

*Lightning!*

Captured by the TV camera 3

Captured by the TV camera 1

Cavity Breakdown at $V_c = 0.90$ MV ($E_{acc} = 3.5$ MV/m)
By the Statistical Analysis

- We have found that such pyrotechnical phenomena are minority in the cavity-breakdown events using those TV cameras.

- What is majority?
Example of Cavity-Breakdown Events (3)

Spot-type explosion of a bright spot which had kept its intensity until the explosion, followed by disappearance

\[ V_c = 0.95 \text{ MV} \quad (E_{\text{acc}} = 3.7 \text{ MV/m}) \]

**Cavity Breakdown!**

Mini-Supernova

\[ T < 0 \]
\[ T = 0 \]
\[ T > 0 \]

No bright spot there!
Example of Cavity-Breakdown Events (4)

*Spot-type explosion without a bright spot*

No bright spot here

Cavity Breakdown!

\[ V_c = 0.65 \text{ MV} \quad (E_{\text{acc}} = 2.5 \text{ MV/m}) \]
Counting Cavity-Breakdown Events for each Category

More than 50% of the cavity-breakdown events are spot-type explosions.

(BS: Bright Spot)
In 20% (or higher) of the cavity-breakdown events, the bright spots exploded, and then disappeared.

### Counting Cavity Breakdown Events for each Category

**(BS: Bright Spot)**

<table>
<thead>
<tr>
<th>Period</th>
<th>BS disappeared</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conditioning</td>
<td>36</td>
</tr>
<tr>
<td></td>
<td>[20.0%] (25.2%)</td>
</tr>
<tr>
<td>Stability test (total)</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>[28.0%] (35.0%)</td>
</tr>
<tr>
<td>Stability test ((V_c = 0.90 \text{ MV}))</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>[45.5%] (55.6%)</td>
</tr>
</tbody>
</table>

**TABLE V:** Number of spot-type explosion events with BSs, where the BSs disappeared after the explosions. The numbers enclosed in square brackets (parentheses) indicate proportions to the total number of the cavity-breakdown events (events with any abnormality observed).
Bright Spots @ $V_c = 0.90$ MV ($E_{acc} = 3.5$ MV/m)

During the RF Conditioning $\rightarrow$ At the beginning of the stability test $\rightarrow$ At the end of the stability test
Bright Spots @ $V_c = 0.90$ MV ($E_{acc} = 3.5$ MV/m)

During the RF Conditioning  ➔ At the beginning of the stability test ➔ At the end of the stability test

- Decrease in the number of bright spots
- Darker and darker

Visual understanding of RF conditioning effects!
Counting Cavity Breakdown Events for each Category

<table>
<thead>
<tr>
<th>Period</th>
<th>Sudden BS appearance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conditioning</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>[3.3%] (4.2%)</td>
</tr>
<tr>
<td>Stability test (total)</td>
<td>0</td>
</tr>
<tr>
<td>Stability test ($V_c = 0.90$ MV)</td>
<td>0</td>
</tr>
</tbody>
</table>

TABLE VI: Number of cavity-breakdown events with sudden BS appearance. The numbers enclosed in square brackets (parentheses) indicate proportions to the total number of the cavity-breakdown events (events with any abnormality observed).

For 3% of the cavity-breakdown events, we observed sudden appearance of bright spots in a time range of the last 2 seconds before the explosions at the breakdowns.
Example of Cavity-Breakdown Events (5)

Spot-type explosion w/o a bright spot which had kept its intensity

V_c = 0.56 MV (E_acc = 2.2 MV/m)

No bright spot here

A new bright spot appeared!

Explosion!

1 frame before

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Example of Cavity-Breakdown Events (6)

V_c = 0.80 MV (E_{acc}=3.1 MV/m)

A tiny bright spot appeared!

Cavity Breakdown!

Explosion!

→ It disappeared.
Example of Cavity-Breakdown Events (7)

46 frames before

$V_c = 0.55 \text{ MV} \ (E_{\text{acc}} = 2.1 \text{ MV/m})$

45 frames (1.5 s) before

A small bright spot appeared!

1 frame before

This bright spot had kept its intensity for 1.5 seconds.

$\rightarrow$ It disappeared.

Cavity Breakdown!

Explosion!
Conclusions on this Breakdown Study
for DR Cavity No.2 (508.9 MHz, CW)

- We observed **clear bright spots** on the endplates during the RF operation.
  - Most of the bright spots had kept their intensity with no significant effects on the RF operation as long as those remaining stable.
  - Even after the RF conditioning (during the stability test with keeping $V_c = 0.90$ MV)

- We have discovered that decrease in the number of bright spots after explosion is a **significant component of RF conditioning** of the cavity.

- We observed **sudden appearance of bright spots** just before breakdowns.
  - The time scale from the sudden appearance to the breakdown is ~1 sec or shorter.
  - Stimulates our interest in microscopic dynamics of generation, growth, and explosion of bright spots and its correlation with conditioning effects and breakdown rates.

- **From the radiation-dose measurements**
  - The total field emission became the minimum level at the end of the RF conditioning (just before the stability test).
  - The bright spots which exploded were not dominant continuous field emitters before the explosions during the stability test.

- **More advanced study** is on-going, supported in part by MEXT KAKENHI Grant-in-Aid for Scientific Research (B).
Thank you for your attention!